Representing interactions between radiation and Earth's surface in large-scale models

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4th ESA EO Summer School on Earth System Monitoring and Modelling
August 4-14, 2008, ESRIN
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Surface Albedo - the coupled land-atmosphere issues and the associated jargon

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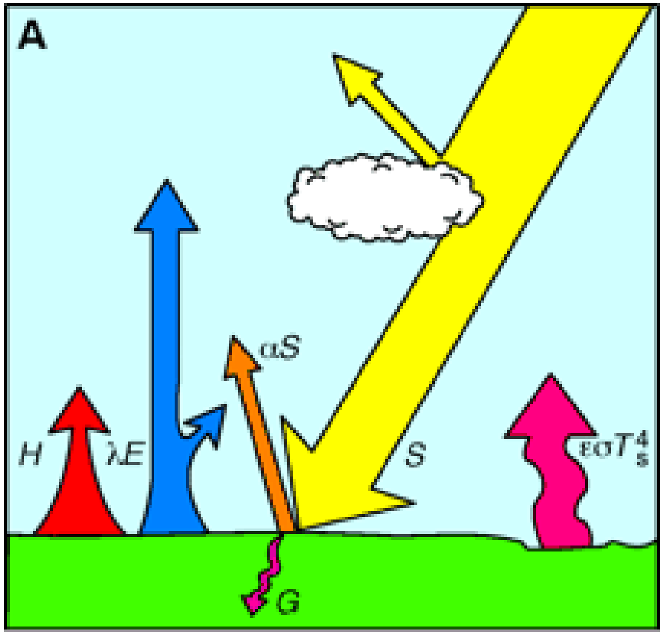
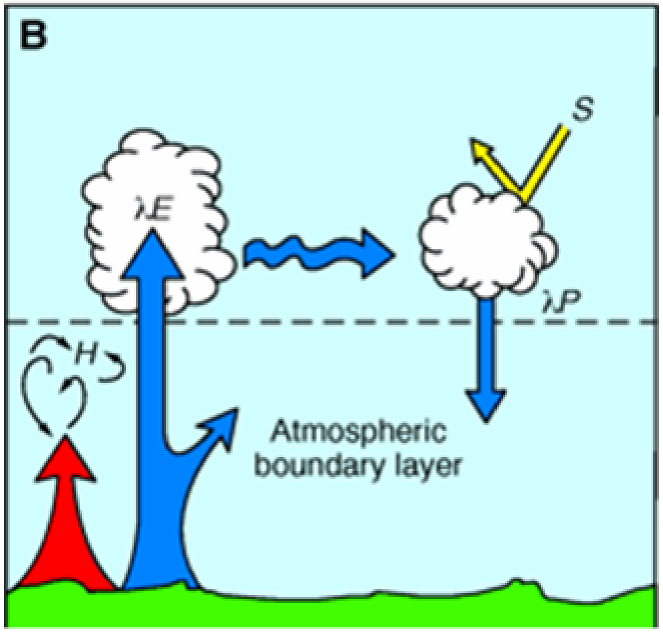
Land-surface coupling



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

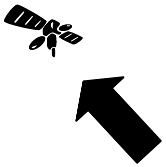
Ref: Sellers et al. (1997) Science, 275, 502-509

Needs of Atmospheric Models with respect to Surface albedo products

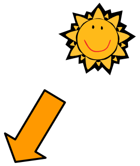
To represent the ratios of upward to downward radiant fluxes, i.e., Albedo, integrated over some spectral domains, e.g., [0.3-0.7] and [0.7-3.0] :

- 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

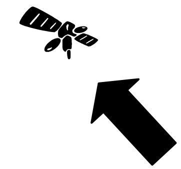
$$I^{\downarrow tot}(z_0,\Omega_0,\Omega';\tau_a,\vec{p}_a)=I^{\downarrow dir}(z_0,\Omega_0,\Omega';\tau_a,\vec{p}_a)+I_B^{\downarrow diff}(z_0,\Omega_0,\Omega';\tau_a,\vec{p}_a)$$

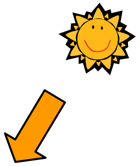
z_0

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

All quantities are monochromatic

Land-surface 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

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

z_0

$$I^{\uparrow}(z_0,\Omega_0,\Omega;\tau_a,\vec{p}_a,\gamma_s,\vec{p}_s) = \frac{1}{\Pi}$$

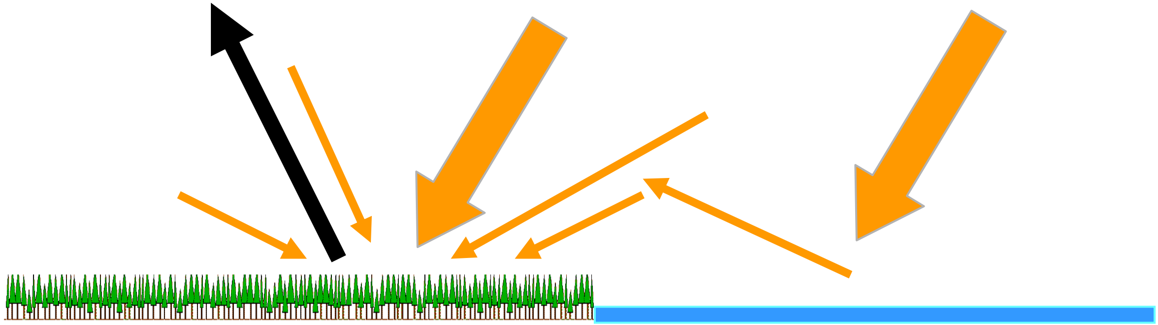
$$\int_{2\Pi} \boxed{\gamma_s(z_0,\Omega'\to\Omega;\vec{p}_s)}.\boxed{I^{\downarrow tot}(z_0,\Omega_0,\Omega';\tau_a,\vec{p}_a,\gamma_s,\vec{p}_s)}\,|\mu'|\,d\Omega'$$

All quantities are monochromatic

The Hemispherical-Directional Reflectance Factor (HDRF)

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

The HDRF can be measured locally in situ and it depends on a number of atmospheric and surface attributes

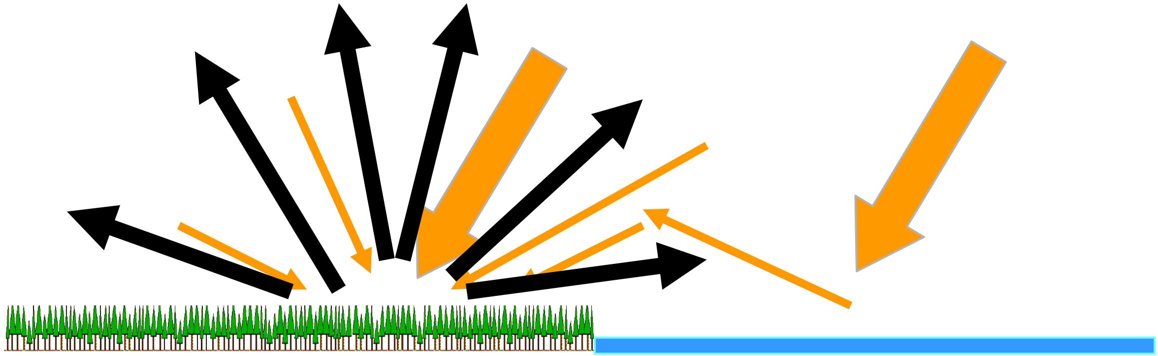


All quantities are monochromatic

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

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

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

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

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

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

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

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

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

assumed isotropic at the bottom of the atmosphere

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

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

All quantities are monochromatic

Usual simplifications and proxies (3)

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

The BRF cannot be measured in situ but in the laboratory

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

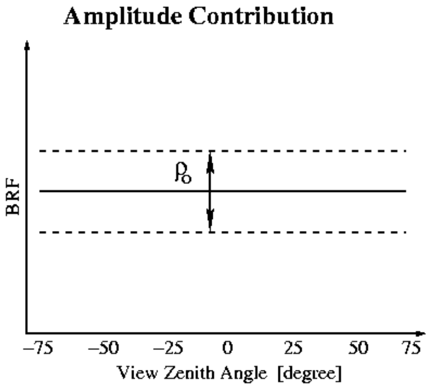
The albedo under isotropic diffuse illumination also called the White Sky Albedo can probably be approximated in situ under overcast conditions

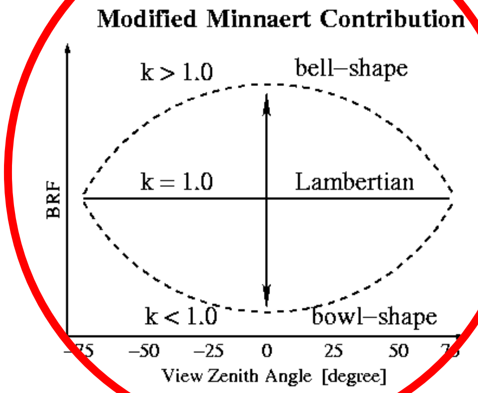
All quantities are monochromatic

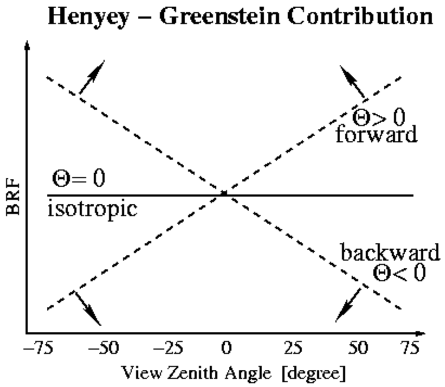
The RPV parametric model

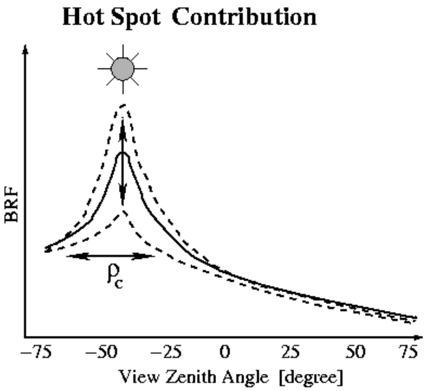
$$BRF(z,\Omega_0 \rightarrow \Omega) = \rho_0 \;\; M_I(k) \;\; F_{HG}(\Theta) \;\; H\,(\rho_c)$$

- ρ_0 - controls amplitude level
- k - controls bowl/bell shape
- Θ - controls forward/backward scattering
- ρ_c - controls hot spot peak


Amplitude Contribution


Modified Minnaert Contribution


Henyey – Greenstein Contribution

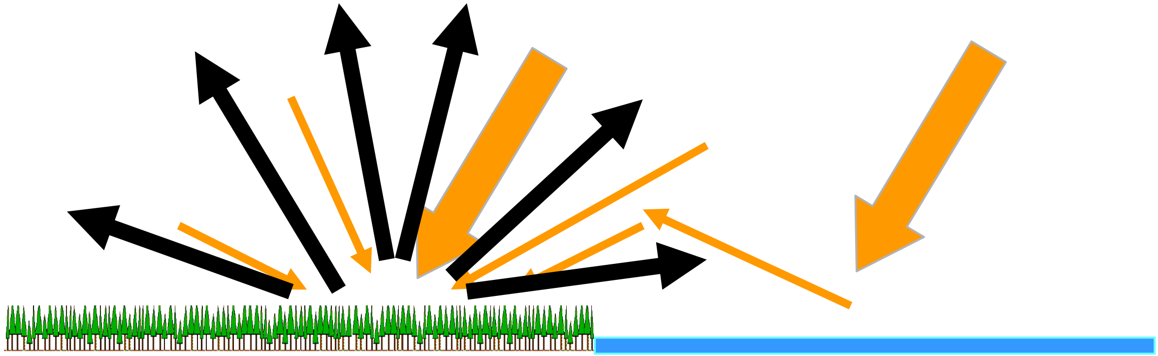

Hot Spot Contribution

Ref: Rahman et al. (1993) JGR

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

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

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

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

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

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

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

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

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

III- Conserving some level of directionality in the incoming diffuse illumination

The 'decoupled' contributions

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

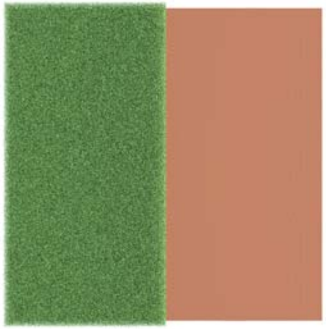
$$+\,\alpha(z_0)\,f_{tot}^{\downarrow diff}(z_0,\Omega_0;\tau_a,\vec{p}_a,\alpha)$$

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

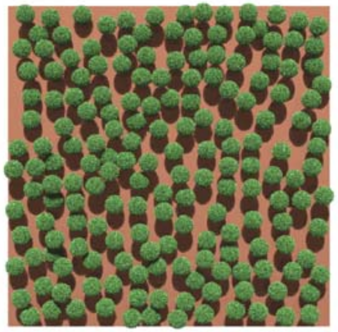
The 'coupled' contribution

All quantities are monochromatic

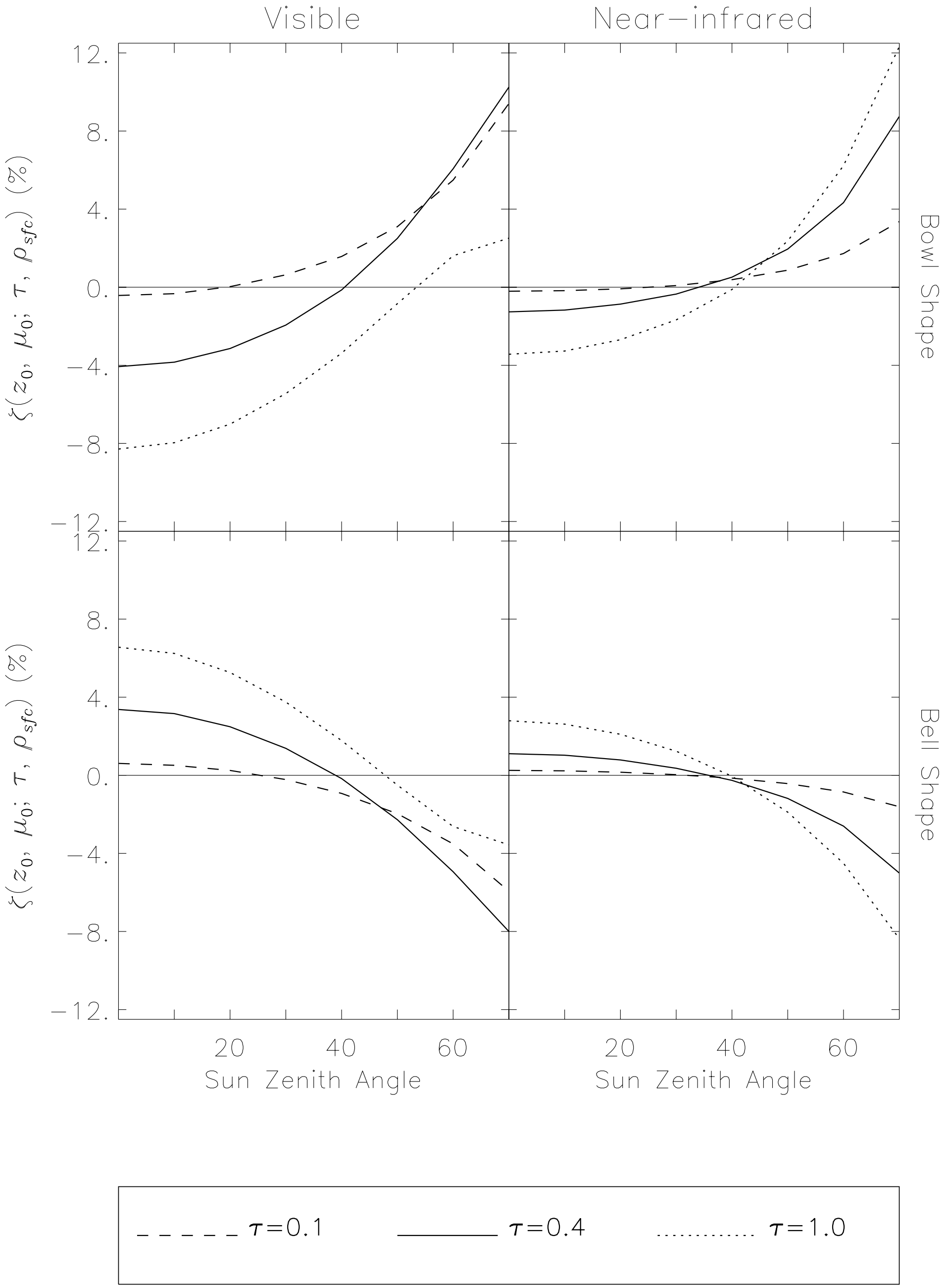
Pinty etal., (2005): Journal of the Atmospheric Sciences



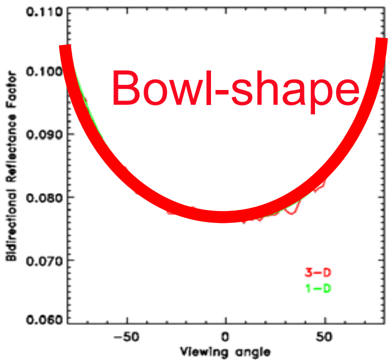
1-D’



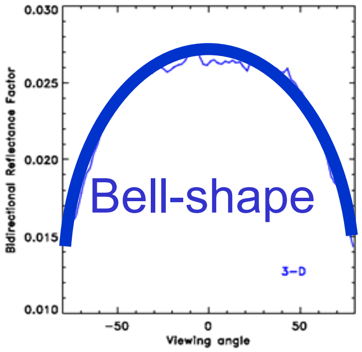
3-D



BRF



BRF



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 complicated 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

Optimal Retrieval of Surface Properties Using Operational Surface Albedo Products

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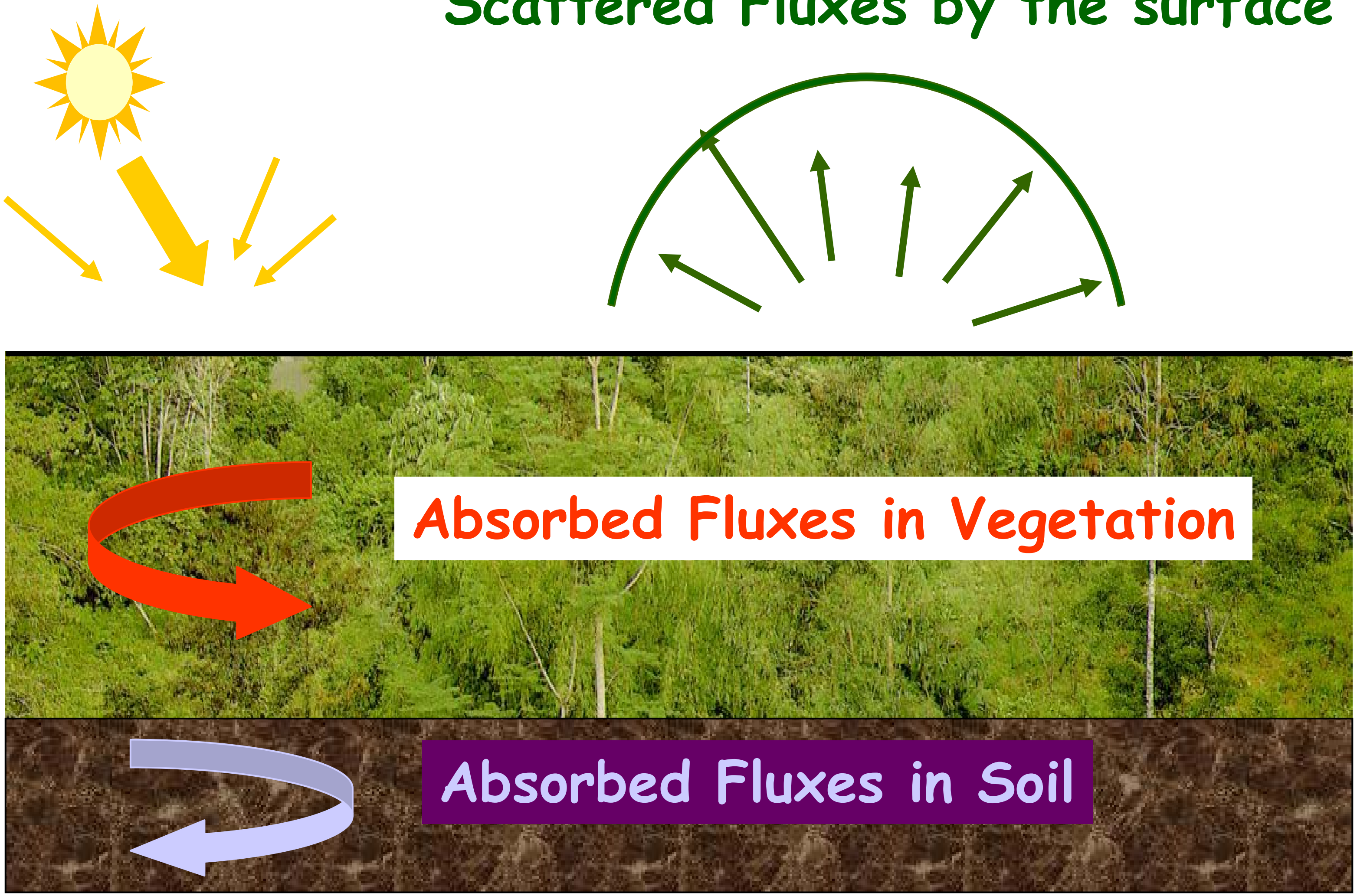
How does radiation redistribute energy between the atmosphere and the biosphere?

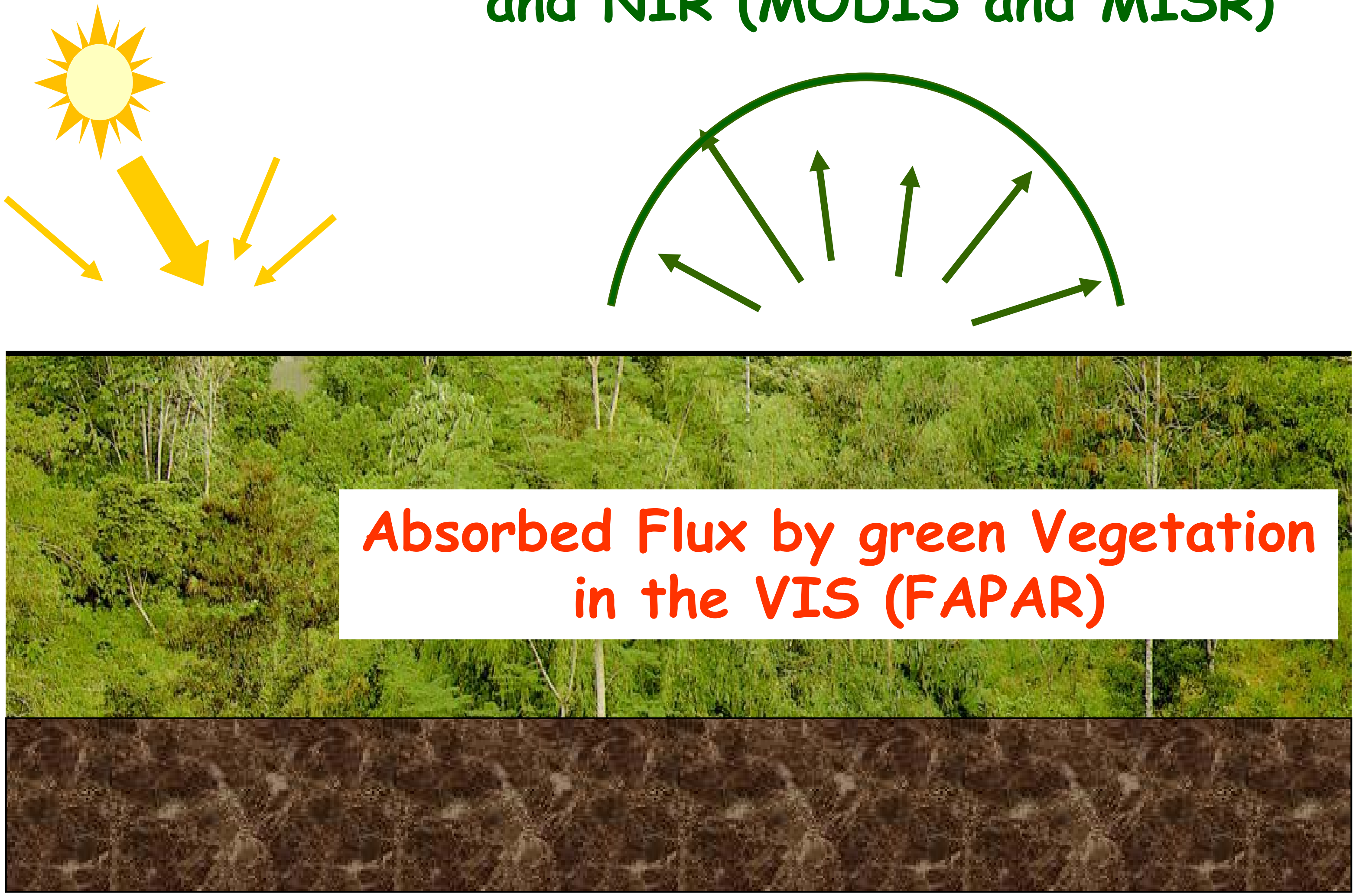


Scattered Fluxes by the surface

Absorbed Fluxes in Vegetation

Absorbed Fluxes in Soil

What do we measure at global scale that we should model as well?



Albedo of the surface in the VIS and NIR (MODIS and MISR)

Absorbed Flux by green Vegetation in the VIS (FAPAR)

How do we model the absorbed fluxes in vegetation and soil ?

Correct partitioning between the flux that is absorbed :

1- in the vegetation layer

$$\overset{\text{VIS}}{A_{\text{veg}}} = 1 - \overset{\text{VIS+NIR}}{ALB_{\text{sfc}}} - A_{\text{ground}}$$

2- in the background

$$A_{\text{ground}} = T_{\text{veg}}(1 - \alpha_{\text{ground}})$$

Assessment of the fraction of solar radiant flux that is scattered (albedo) by, transmitted through and absorbed in the vegetation layer

Pinty etal., (2006): Journal of Geophysical Research, doi:10.1029/2005JD00595

What are the needs?

- Update/improve the current Land Surface schemes describing the radiation transfer processes in vegetation canopies

  see 2-stream model by Pinty et al. JGR (2006).

Requirements from a 2-stream model

- 3 (effective) state variables:

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

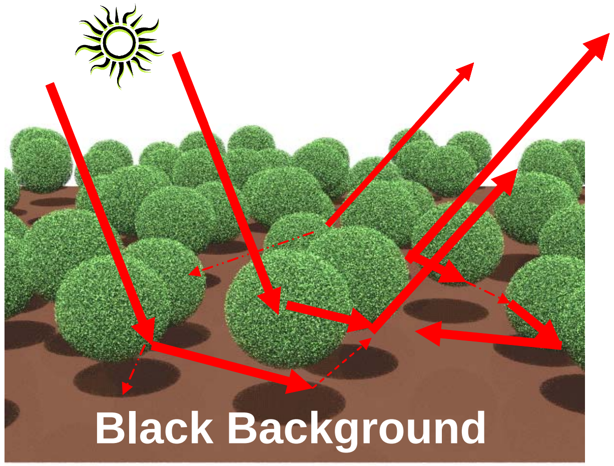
- 2 boundary conditions:

1. *Top: Direct and Diffuse atmospheric fluxes (known)*
2. *Bottom : Flux from background Albedo (unknown)*

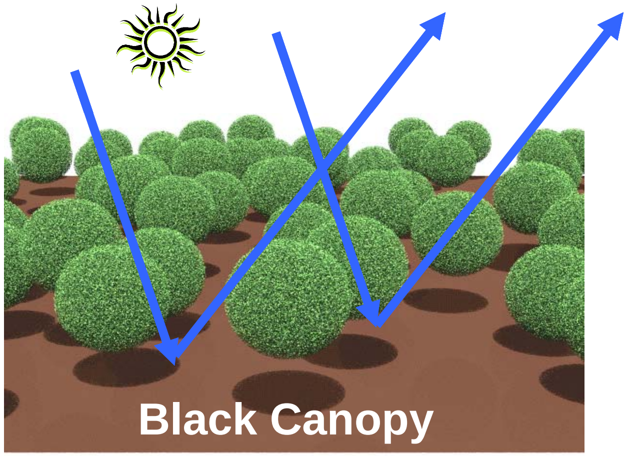
Pinty etal., (2006): Journal of Geophysical Research, doi:10.1029/2005JD00595

Decompose the complex problem into simpler problems to solve

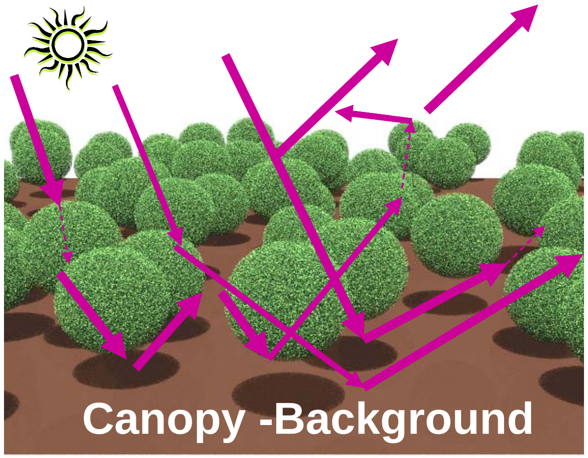
$$DHR(z_0,\mu_0;\rho_{sfc}) = DHR^{Collided}_{vegetation}(z_0,\mu_0;\rho_{sfc}) + \rho_{sfc}\left[\overset{\smile}{DHR}{}^{Uncollided}_{background}(z_0,\mu_0)\right] + \rho_{sfc}\left[\overset{\smile}{DHR}{}^{Collided}_{background}(z_0,\mu_0;\rho_{sfc})\right]$$



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



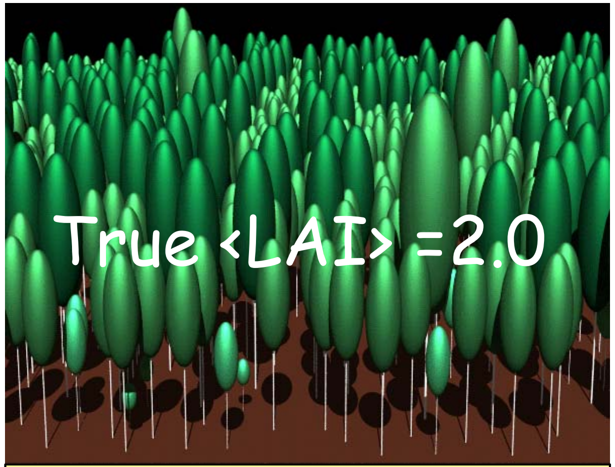
- No absorption process by vegetation associated with this wavelength-independent contribution
- Strongly controlled by 3-D distribution of vegetation architecture



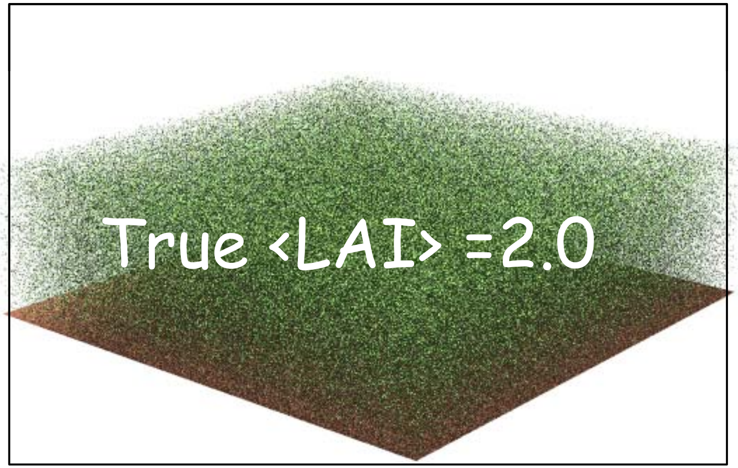
- Controlled by multiple scattering events between the background and the canopy
- Mostly negligible contribution in the visible domain of the solar spectrum

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

The concept of effective LAI



3-D heterogeneous system



1-D system representation

Direct transmission at 30 degrees Sun zenith angle,

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

Direct transmission at 30 degrees Sun zenith angle,

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

Effects induced by internal variability of LAI

What are the needs?

- Update/improve the current Land Surface schemes describing the radiation transfer processes in vegetation canopies

  see 2-stream model by Pinty et al. JGR (2006).

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

  Retrieve 2-stream model parameters from RS flux products

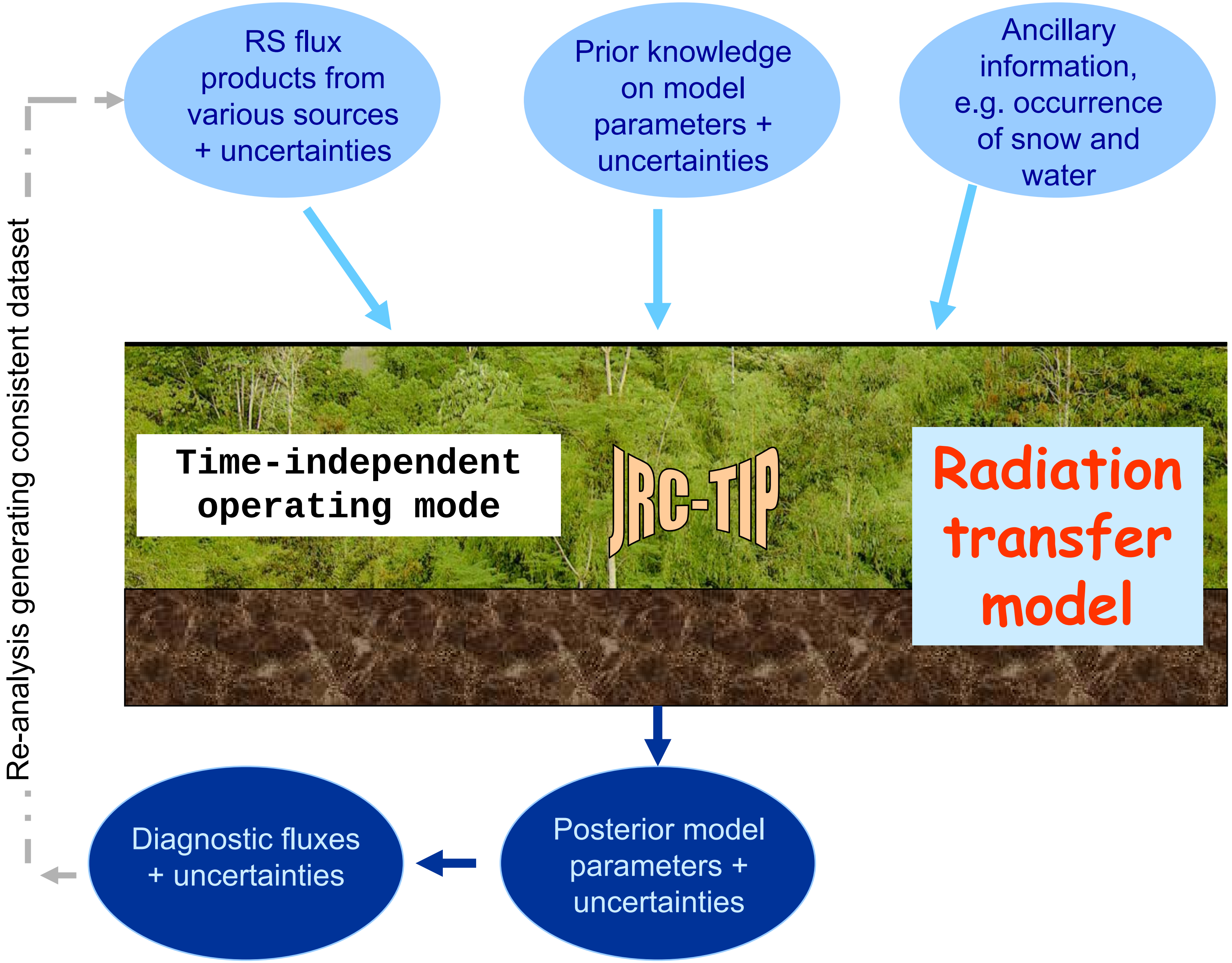
The same RT models must be used in inverse mode and in forward mode to ensure consistency between RS products and large scale models's simulations

Retrievals of model Parameters for Land surface schemes

The inverse problem can be formulated in order to find solutions **optimizing all the available information** i.e., inferring statistically the state of the system

Towards an **integrated system** for the optimal use of remote sensing flux products

JRC-Two-stream Inversion Package: JRC-TIP



RS flux products from various sources + uncertainties

Prior knowledge on model parameters + uncertainties

Ancillary information, e.g. occurrence of snow and water

Time-independent operating mode

JRC-TIP

Radiation transfer model

Posterior model parameters + uncertainties

Diagnostic fluxes + uncertainties

Re-analysis generating consistent dataset

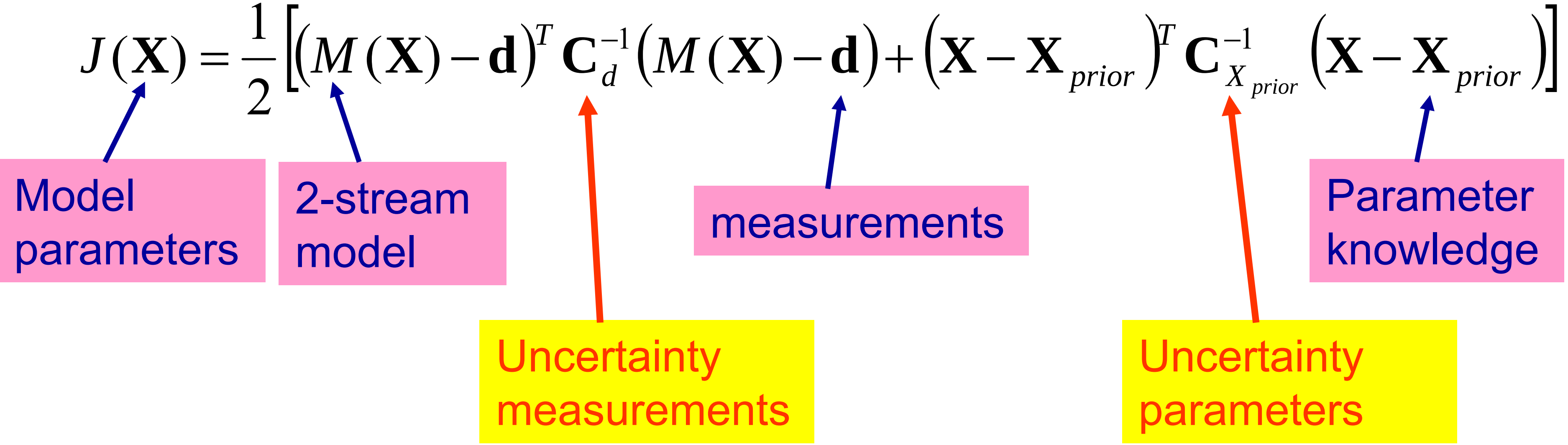
INPUTS : prior knowledge

- RS Flux products, e.g., Albedo Vis/NIR and/or FAPAR noted $\mathbf{d}$
- Updated/benchmarked 2-stream model from Pinty et al. JGR (2006) noted $M(\mathbf{X})$
- A priori knowldege/guess on model parameters noted $\mathbf{X}_{prior}$

uncertainty on the RS products is specified in the measurement set covariance matrix $\mathbf{C}_d$

uncertainty associated the model parameter is specified via a covariance matrix $\mathbf{C}_{X_{prior}}$

The core of the JRC-TIP



$$J(\mathbf{X}) = \frac{1}{2}\left[\left(M(\mathbf{X})-\mathbf{d}\right)^T \mathbf{C}_d^{-1}\left(M(\mathbf{X})-\mathbf{d}\right)+\left(\mathbf{X}-\mathbf{X}_{prior}\right)^T \mathbf{C}_{X_{prior}}^{-1}\left(\mathbf{X}-\mathbf{X}_{prior}\right)\right]$$

Model parameters

2-stream model

measurements

Parameter knowledge

Uncertainty measurements

Uncertainty parameters

- Computer optimized Adjoint and Hessian model of cost function from automatic differentiation technique
- Assume Gaussian theory
- Posterior uncertainties on retrieved parameters are estimated from the curvature of $J(\mathbf{X})$

Pinty etal., (2007): Journal of Geophysical Research, *in pres*

OUTPUTS: posterior knowledge

- PDFs of all 2-stream model parameters:

$$PDF(\mathbf{X}) \approx \exp\left(-\frac{1}{2} (\mathbf{X} - \mathbf{X}_{post})^T \mathbf{C}_{X_{post}}^{-1} (\mathbf{X} - \mathbf{X}_{post}) \right)$$

a posteriori uncertainty covariance matrix

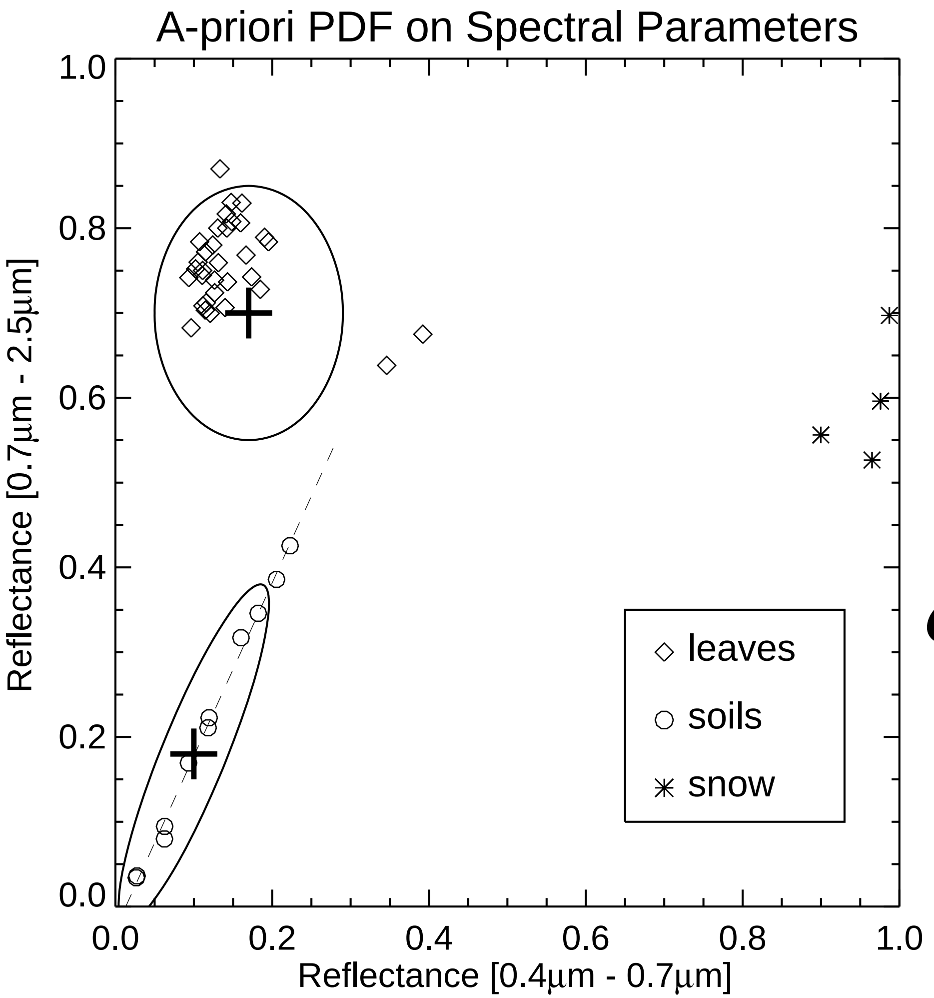
- Assessement of all fluxes predicted by the 2-stream model and their associated uncertainty:

$$\mathbf{C}_{post}^{Flux} = \mathbf{G}\mathbf{C}_{X_{post}}\mathbf{G}^T$$

Pinty etal., (2007): Journal of Geophysical Research, *in pres*

Application results against model-based standard scenarios

a priori knowledge on model parameters



$$LAI_{prior} = 1.5$$

$$\sigma_{prior}(LAI) = 5.0$$

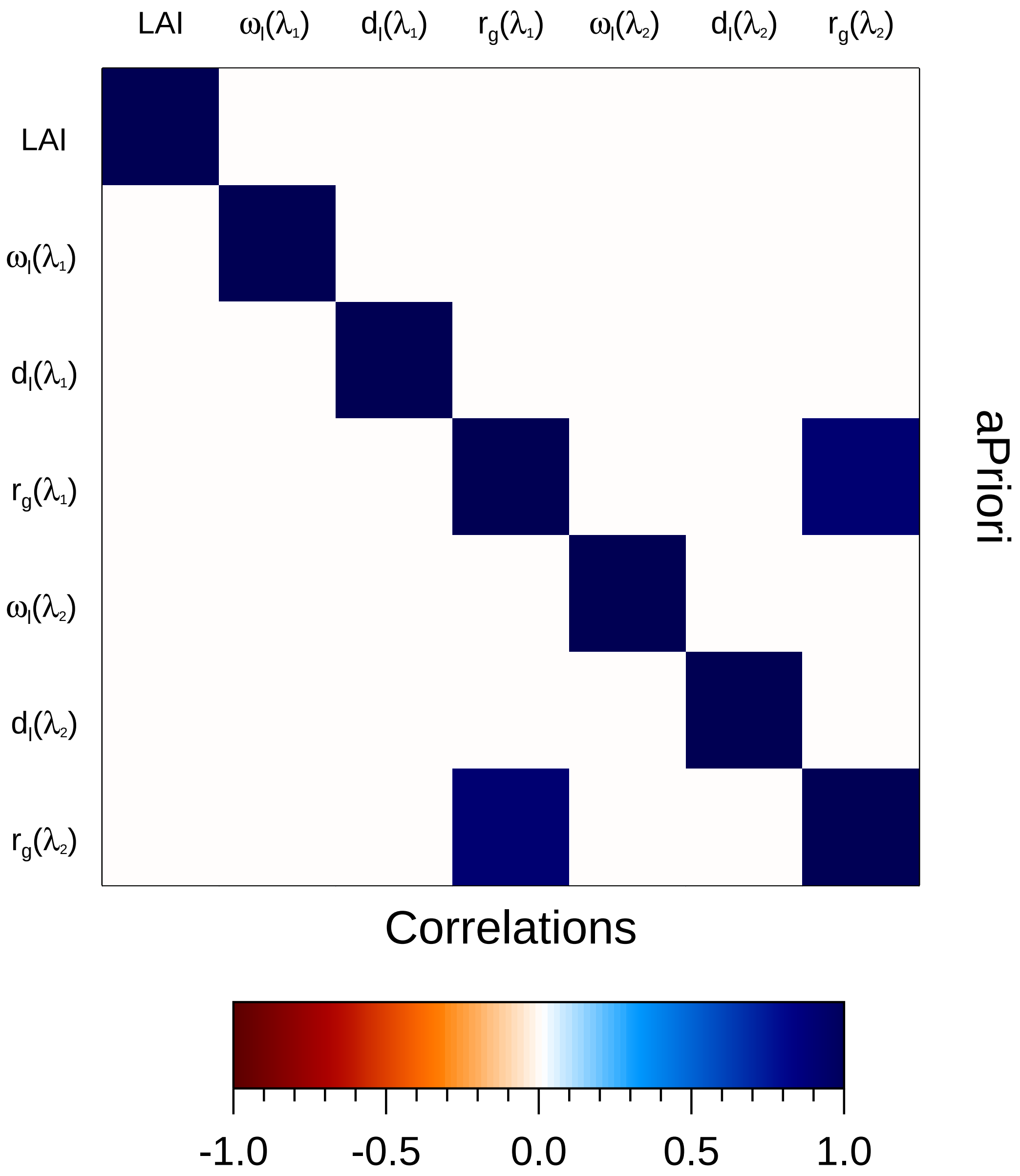
Pinty etal., (2007): Journal of Geophysical Research, *in pres*

Application results against model-based standard scenarios

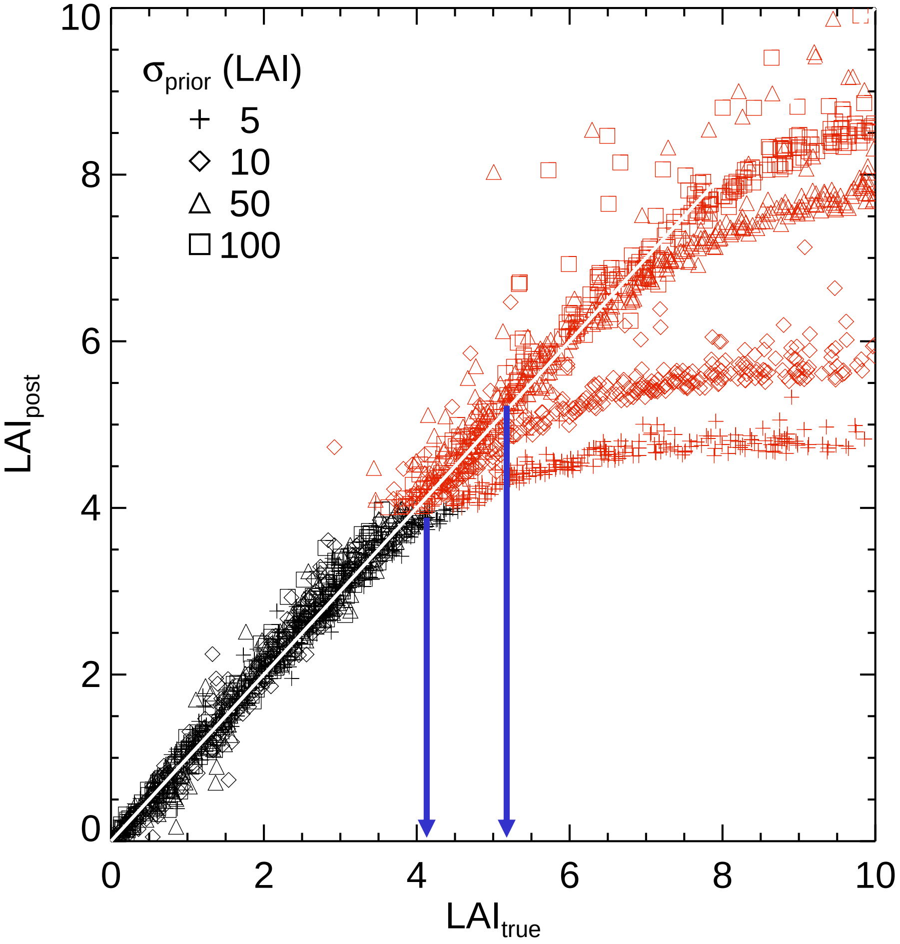
Application with measurements set **d** including various combinations of visible and near-infrared broadband radiant fluxes, i. e., Albedo (R), Transmission (T) and Absorption (A)

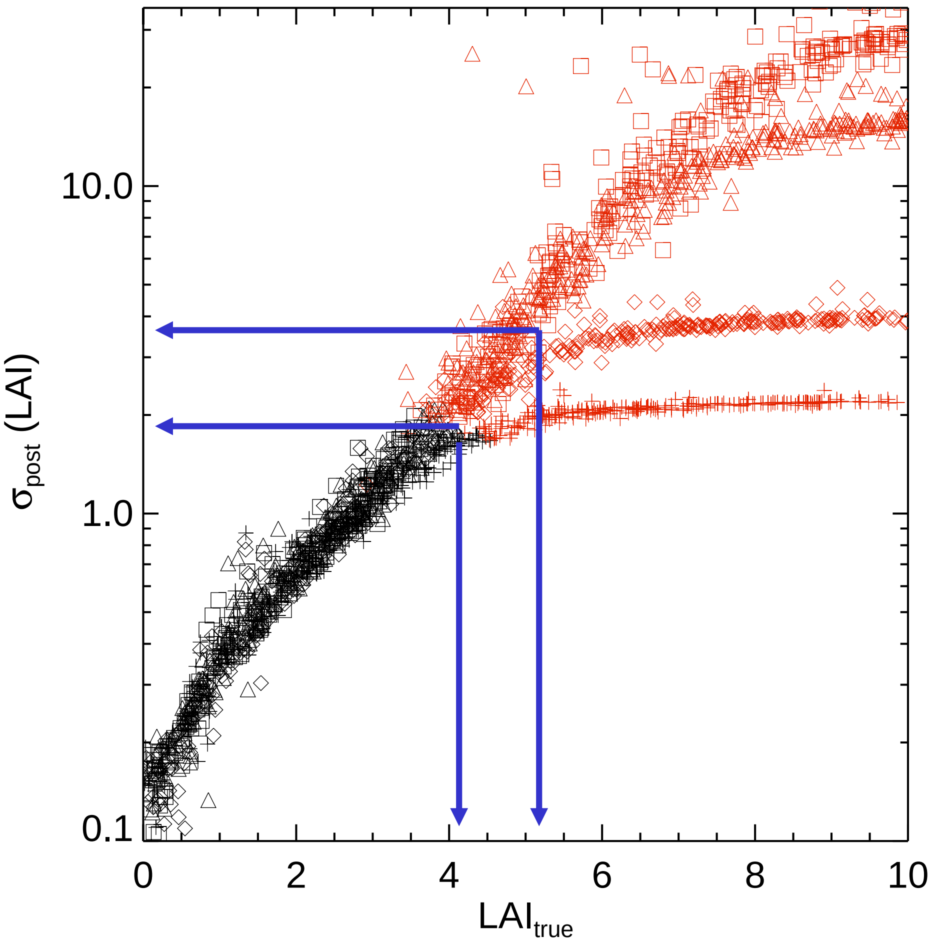
PDFs for 7 model parameters to be estimated: LAI, Leaf and background properties in the two spectral domains

a priori covariance matrix



Retrieval of LAI (model-based cases)

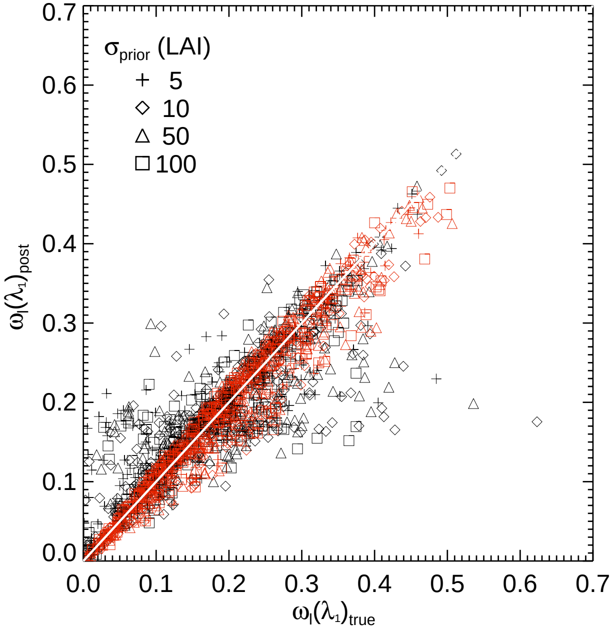


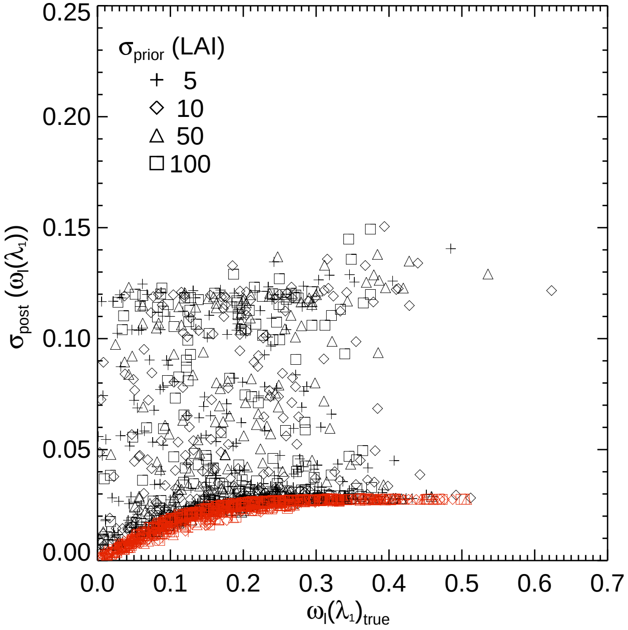


$$\sigma_{post}(LAI) \simeq 0.35 \times LAI_{post}$$

Retrievals in Visible domain

Single scattering albedo

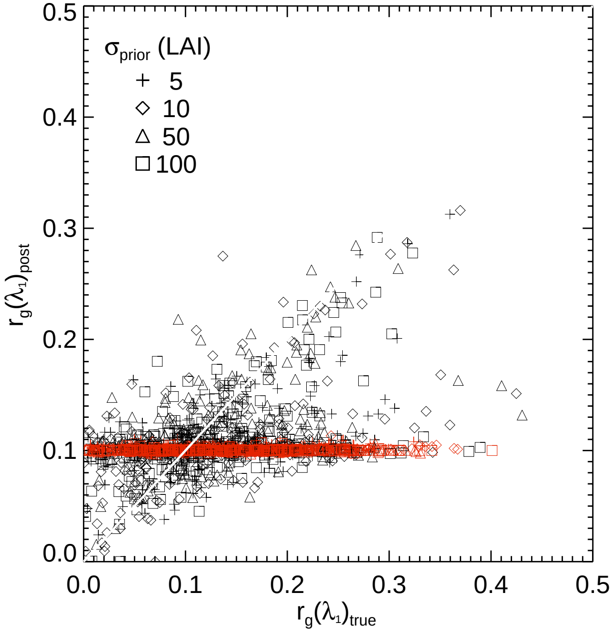


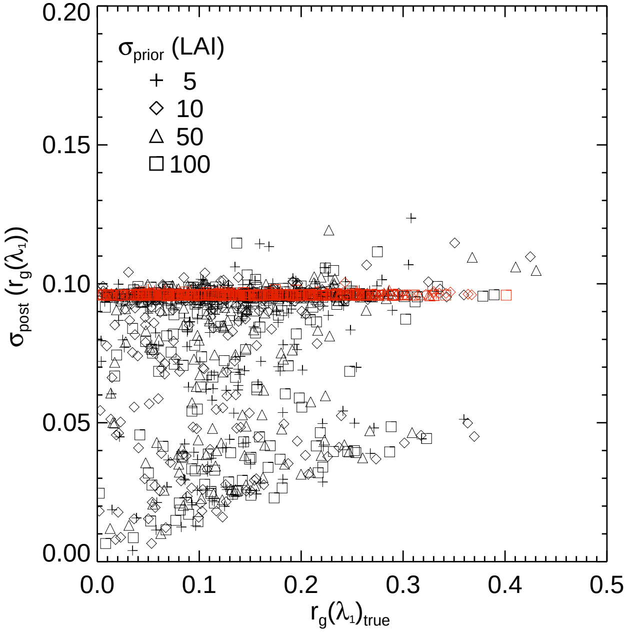


LAI<4

LAI>4

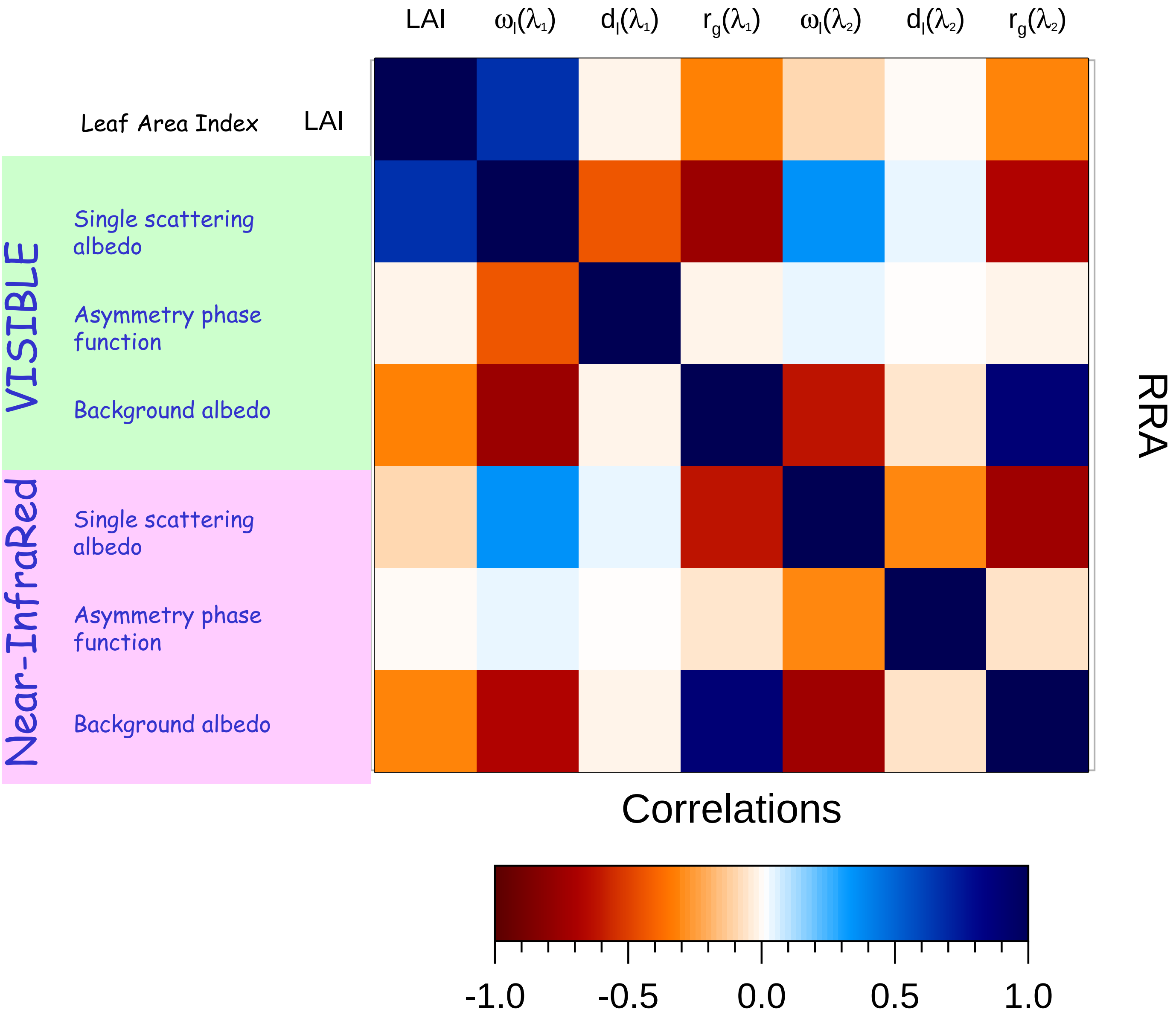
Background albedo





RRA

a posteriori covariance matrices



Using the absorbed and scattered flux only

Concluding remarks

1. "Surface albedo" covers different physical quantities: great care is recommended when using such values from various providers

2. Computer efficient inversion package has been designed and tested : estimate of uncertainty on all retrievals including correlations

3. This integrated package can be used for various purposes : retrieval of parameters from RS products, validation of RS products, assimilation of RS products into Land surface schemes.