Quantifying cloud/radiation uncertainties to better understand radiative closure assessments

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PhD on 3D clouds and radiation, from Monte Carlo simulations in LES to parameterizations for large scale models (2016-2019). On board of CARDINAL as a postdoc since August 2021, in Paris until end of June 2022; then move to Canada?

The two scientific questions I investigate in the context of CARDINAL:

1. How do 3D radiative effects of clouds affect L2-algorithms performance?
2. How do uncertainties in geophysical parameters propagate through radiation?

WP-0210 Processor development and verification
WP-0420 Scientific performance assessment

1.1 L2-agorithms assessment and the 3D radiative effects of clouds

The current assessment of L2 retrievals is based on synthetic observations produced by 1D radiative transfer models run on LES outputs

In real world, light propagates in 3D and photons that reach the sensors might have been emitted or reflected by the atmosphere a few kilometers away from the scene. This makes the measurements difficult to interpret.

In the presence of heterogeneous clouds, the mock-up inputs are biased by the neglect of horizontal transport between LES columns.

How would L2-retrieval algorithms perform given mock-up observations based on 3D radiative transfer?

1.2 Introducing 3D simulations in the assessment chain

Available tools and included features

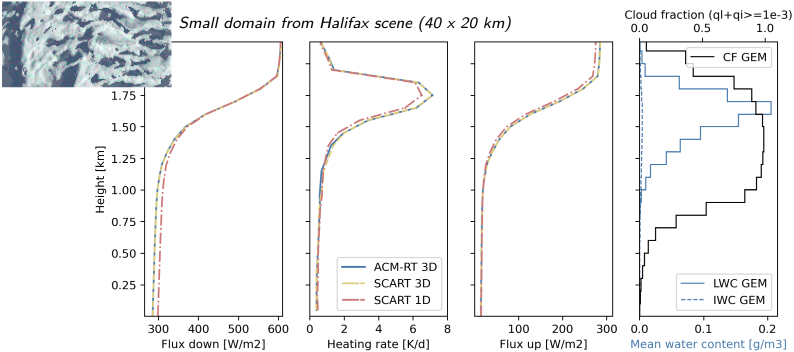
MC model	ACM-RT	SCART	htrdr
Inputs	1D+2D	3D	3D
Constituents	Liquid/Ice/Aerosols	Liquid/Ice	Liquid
Droplet size	3D	Constant	Constant
Phase funct	Mie	Mie	Henyey-Greenstein
Gas	3D	1D	1D
Spectral integ.	Broadband	Broadband or mono	Any interval
Sources	Solar / Thermal	Solar	Solar / Thermal
Solvers 1D/3D	RRTM / MC	MC / MC	- / MC
Flux / BBR / MSI	+ / + / -	+ / $\sim$ / $\sim$	- / + / +

ACM-RT: not adapted to LES inputs, not efficient for high spatial resolution
SCART: no thermal solver, not efficient for high spatial resolution
htrdr: no 1D solver, no ice or aerosols, efficient but no flux profiles

First idea: convert 3D LES fields into the format expected by ACM-RT (ACM-COM + ACM-3D format).

1.2 Introducing 3D simulations in the assessment chain

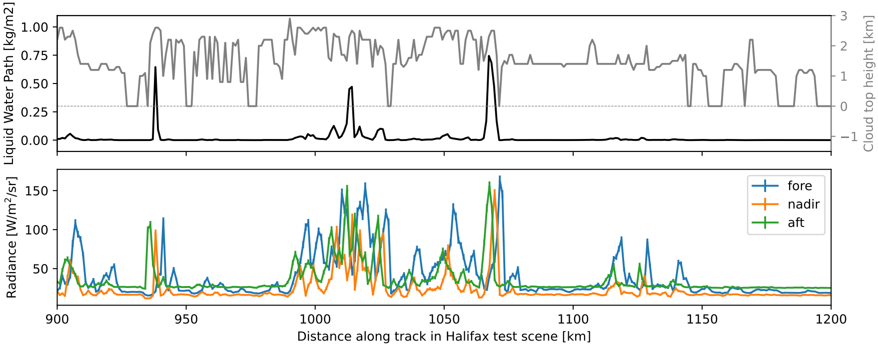
Comparing ACM-RT and SCART fluxes to verify the LES to ACM-COM + ACM-3D routines. Found bugs in both codes, until eventually agreeing!



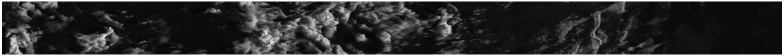
An important result as MC codes are difficult to validate on realistic cases.

But quite complex conversion procedure and memory consuming... ACM-RT not very adapted for high res radiances on large domains $\Rightarrow$ changing strategy

1.2 Introducing 3D simulations in the assessment chain (htrdr estimates)



Fore view solar broadband <



← sun

sza 60°

Nadir view solar broadband ^

← sun

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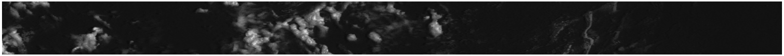

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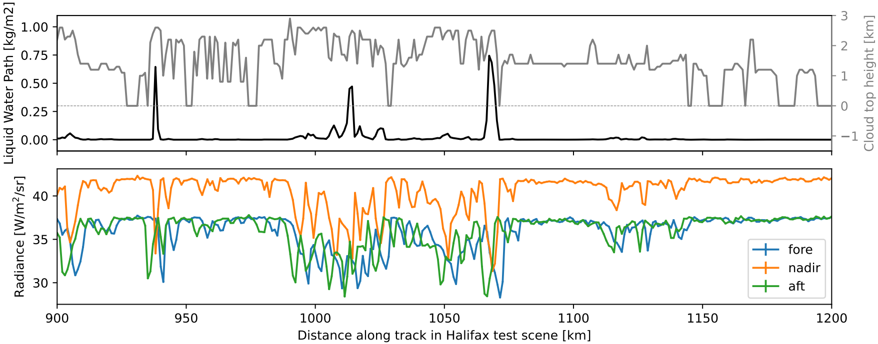
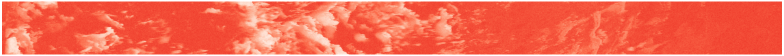


Fore view thermal broadband <



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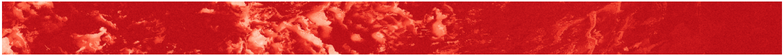


Aft view thermal broadband >

1.3 Ongoing and future work

None of the available tools were ready for use, need to decide where to invest.
Learned that it is easier to add features than to change design
$\Rightarrow$ htrdr seems to be the best choice although no "1D" counterpart.

$\triangleright$ Run first tests on "idealized" cases while further developments are made? How realistic do 3D RT simulations need to be to properly test the different products?

$\triangleright$ Current capability of htrdr enough to assess the colocating part of the BMA-FLX product and estimate the typical errors we can expect in heterogeneous cloud scenes? Reference height for upward flux estimates? Ongoing discussions with GMV and RMIB.

$\triangleright$ Cloud and aerosol properties? First quantify the errors and if relevant, think of a correction that could be applied (phase 2). Coherence of RT assumptions made in passive and active sensor simulations?

2.1 Radiative closure assessment and uncertainties

The radiative closure assessment will provide information on the quality of the L2 products, with the objective of the difference between observed and simulated radiation being less than 10 W/m^2.

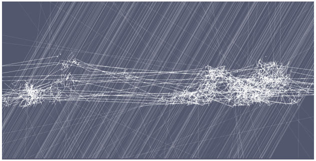
Many uncertainties remain in the system: in the geophysical retrievals, for instance associated to the 3D radiative effects of clouds; in the non-retrieved parameters such as surface properties that might affect both simulated and retrieved fluxes; and in the retrieved fluxes for instance due to colocating uncertainties.

These uncertainties should be taken into account in the radiative closure assessment to better inform on the quality of L2 products, ideally to identify probable sources of error

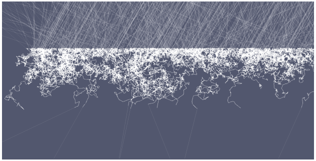
How do uncertainties in geophysical parameters impact simulated radiative fluxes?

2.2 Monte Carlo methods and uncertainty propagation

Monte Carlo methods traditionally produce mean radiative estimates given known atmospheric state by tracking photon paths throughout small-scale light–matter interactions. Since the paths explore the medium in details, they contain much more information than what is usually extracted.



Solar paths sampled in a cumulus field



Solar paths sampled in a slab

Idea: make better use of this information!

Principles:

▷ a perturbation of state will result in a modification of the path probabilities
▷ a set of paths sampled according to a "reference state" can be "corrected" afterwards to account for state perturbation
▷ depending on the type of parameter and amplitude of the perturbation, the variance of the "corrected" sample might be high

2.2 Monte Carlo methods and uncertainty propagation

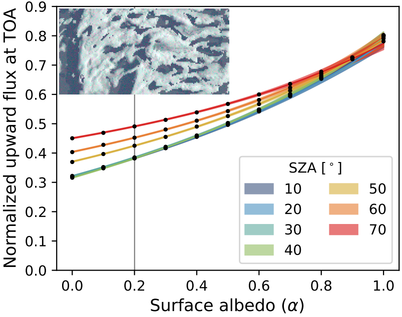
Investigating a new method called Functional Monte Carlo. Reformulating the problem to express fluxes as a function of chosen parameter, here surface aledbo α:

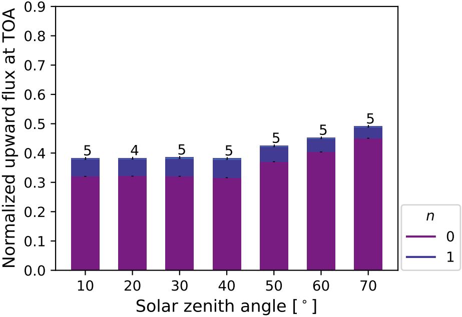
$$F(\alpha) = \sum_{n=0}^{\infty} F_{n|\hat{\alpha}} \left(\frac{\alpha}{\hat{\alpha}}\right)^n$$

$\hat{\alpha}$ is the "reference" albedo

n is the number of reflections

and using a single Monte Carlo simulation to estimate the coefficients of the polynomial $(F_n)_n \Rightarrow$ the polynomial can then be evaluated for any value of α.





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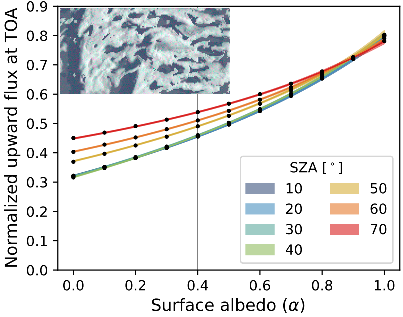

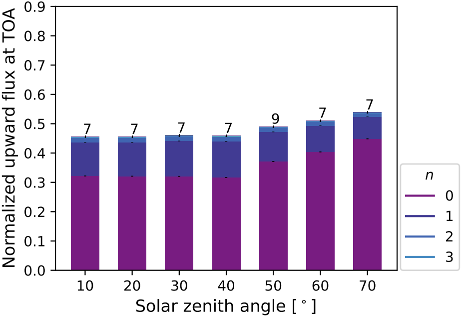

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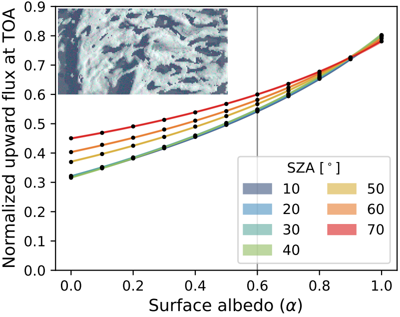

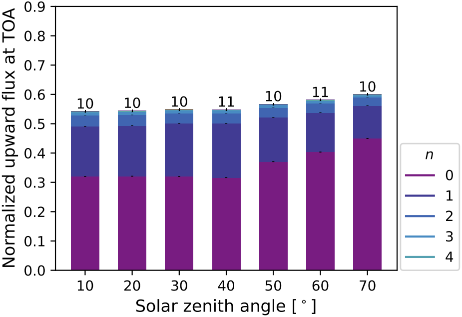

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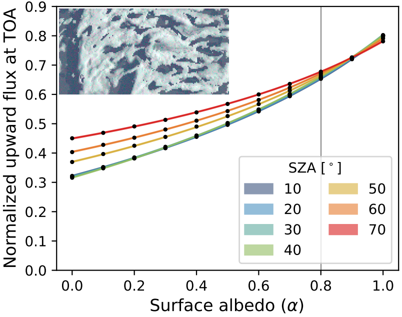

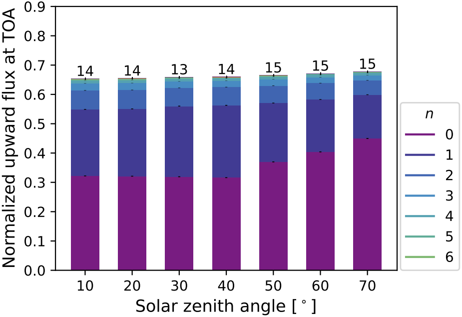

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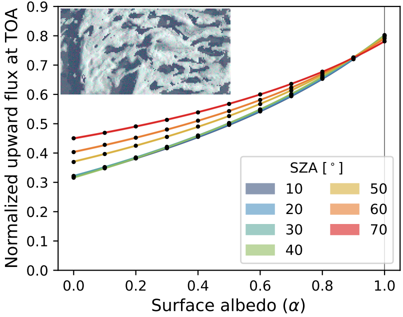
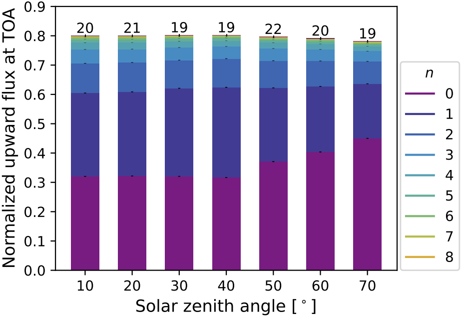
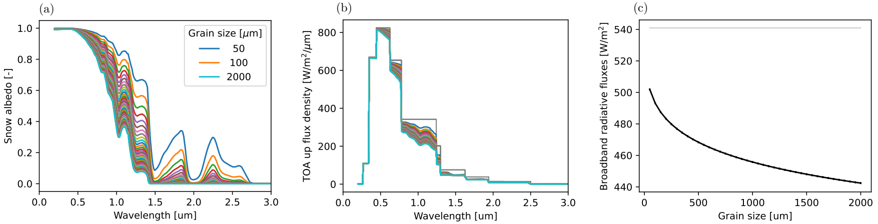




2.2 Monte Carlo methods and uncertainty propagation

Now let the surface albedo itself depend on physical parameters, for instance on snow grain size. **(a)** A change in snow grain size will impact the whole spectral features of surface albedo. Sorting the paths per spectral band, one polynomial function is estimated for each band. **(b)** The polynomials can then be evaluated for any value of snow grain size and **(c)** averaged over the spectrum to produce broadband flux estimates for large numbers of snow grain sizes.



Albedo as a function of snow grain radius from Kokhanovsky and Zege (2004), RRTM-G bands in solar spectrum

$\Rightarrow$ From a single MC simulation, we obtain $\Delta F = f(\Delta parameter)$

2.2 Monte Carlo methods and uncertainty propagation

Extending the Functional Monte Carlo method to cloud parameters?
▷ high-dimensional functional
▷ large amounts of data to store
▷ probably large variance

If the distribution of state perturbations is known in advance: explore randomly perturbed states?

▷ Independent MC simulations in randomly perturbed media (Howard); computationally expensive hence probably not doable in EarthCare

▷ Or use a single path sample to simultaneously compute the mean and variance of radiative estimates corresponding to the distribution of perturbed states, by applying path-weight corrections on the fly (as would be done in traditional importance sampling). This remains to be explored!

2.3 Ongoing and future work

▷ Finalization of a publication on the Functional Monte Carlo method with Howard

▷ Combine the random perturbation method implemented by Howard with an original path-weight correction method for perturbed cloud water contents and hydrometeor effective sizes

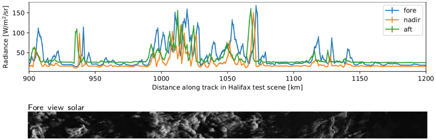
▷ Investigate the practicality of these new methods to efficiently assess flux uncertainties given uncertainties in cloud parameters that are on the order of existing errors in L2 algorithms, and of errors due to neglecting 3D effects.

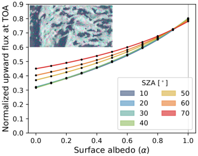
Quantifying cloud/radiation uncertainties to better understand radiative closure assessments

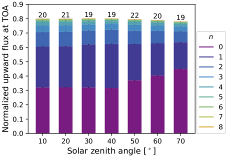
In summary,

1. More technical developments and ongoing work than answers so far! Hopefully first tests of L2 algorithms based on 3D RT simulations coming soon...

2. Leveraging Monte Carlo expensive path tracking to extract new information!







Thanks! Questions?