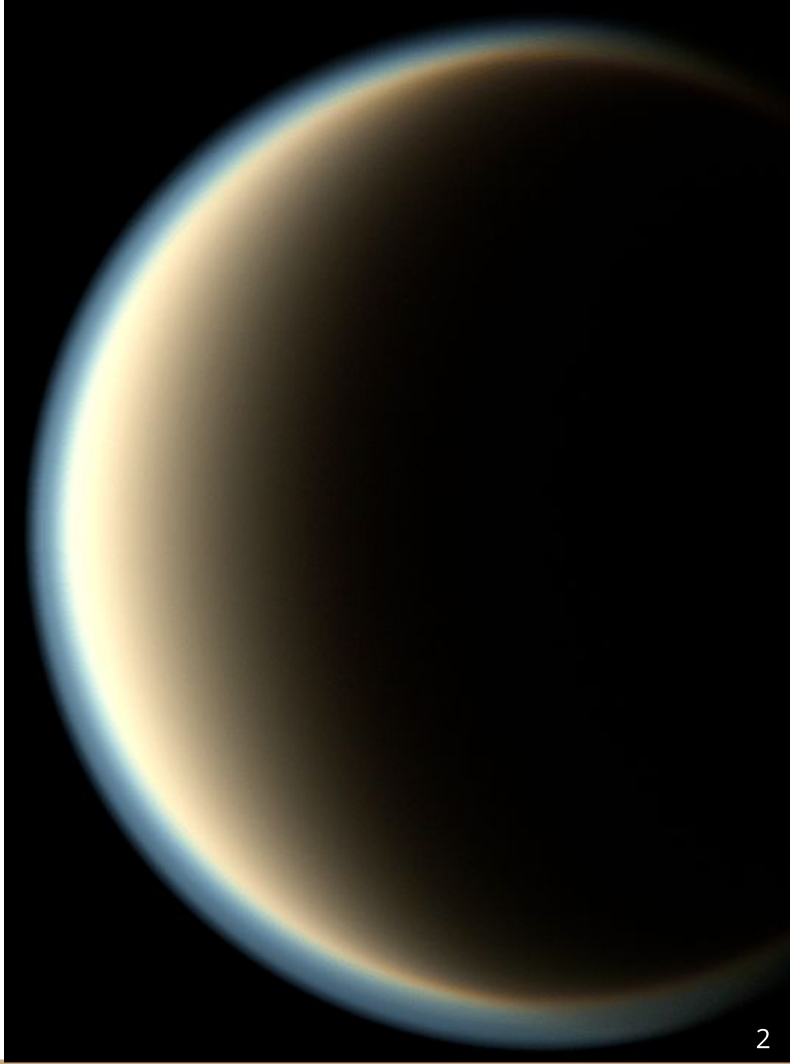
Is Titan flat?
Coupling a 3D Monte Carlo radiative transfer model with the Titan PCM

Anthony Arfaux, Sandrine Vinatier, Pascal Rannou, Sébastien Lebonnois, Vincent Eymet, Vincent Forest, Zili He, Ehouarn Millour, Bruno de Batz de Trenquelléon, Clément Petetin

23/06/2026, Journées de la SF2A, Grenoble

Introduction to Titan

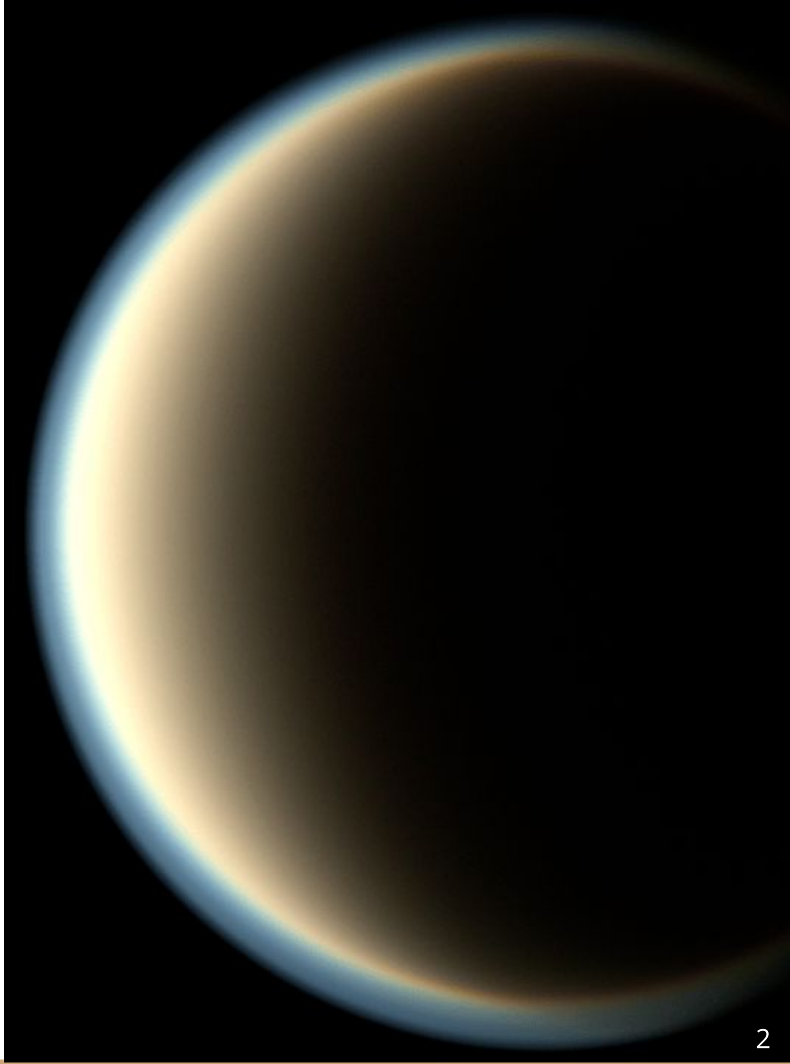
Largest moon of Saturn: 2575 km radius



Introduction to Titan

Largest moon of Saturn: 2575 km radius

Thick atmosphere: ~1000 km



Introduction to Titan

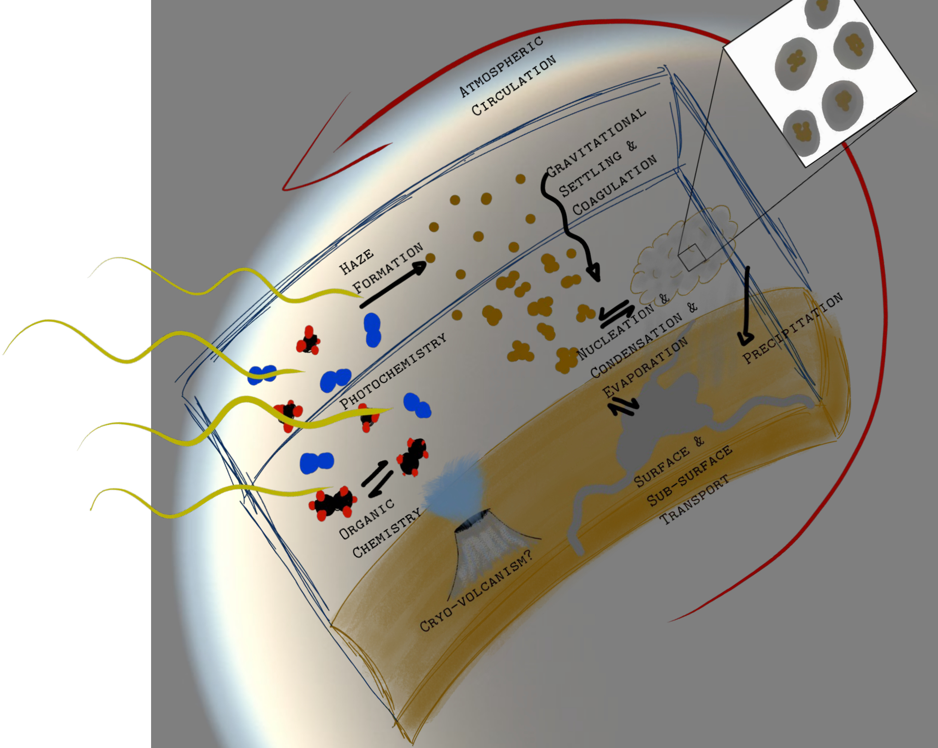
Largest moon of Saturn: 2575 km radius

Thick atmosphere: ~1000 km

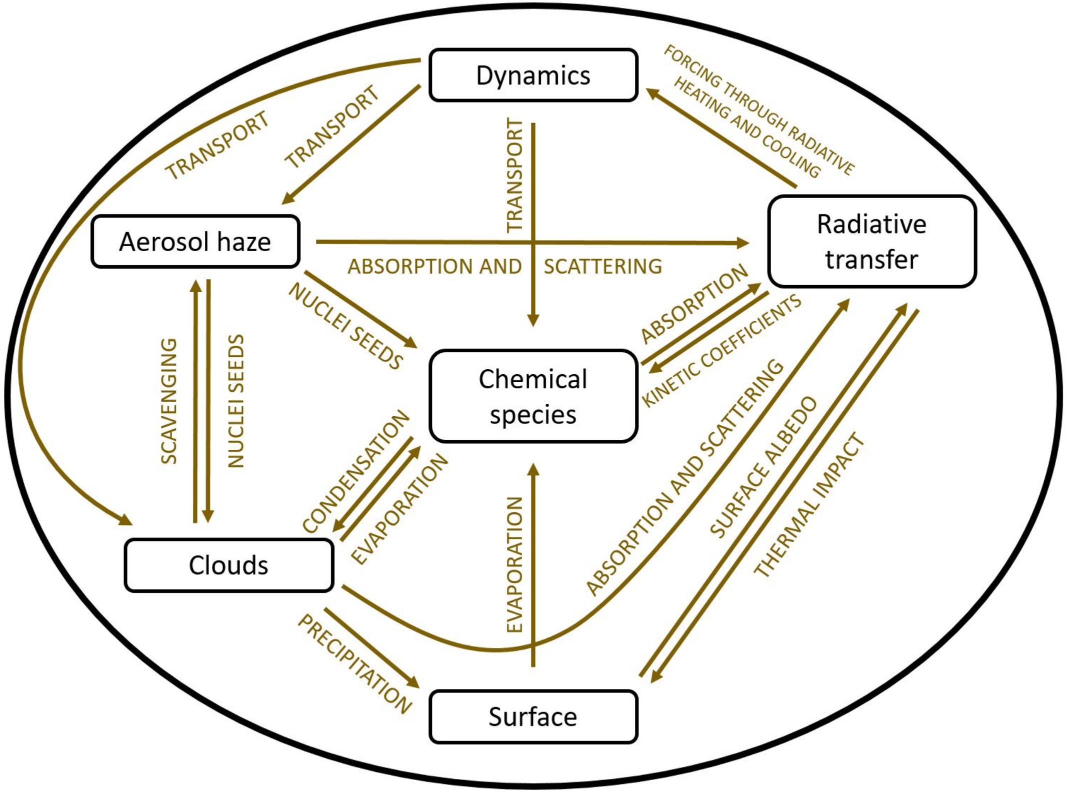
Surface pressure: 1.5 bar

Composition: N_2(94-98 %), CH_4(1-5 %)

$CH_4 \Rightarrow$ Haze and clouds

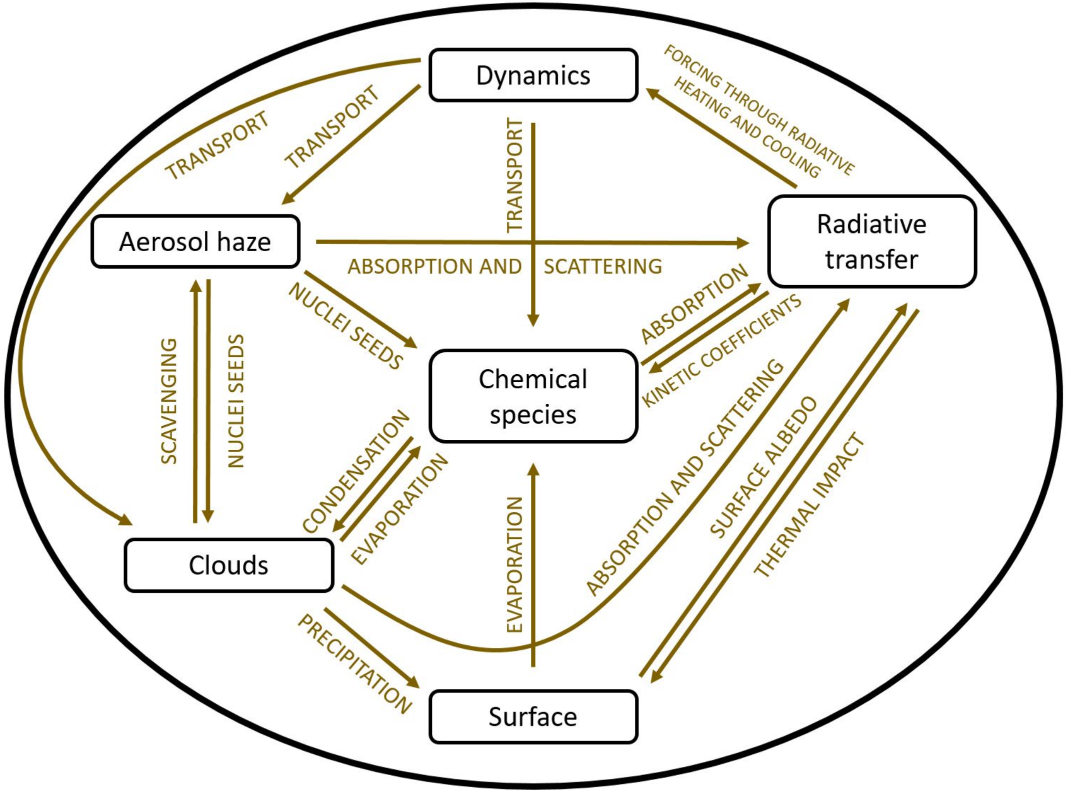


Titan LMDZ Planetary Climate Model



Titan LMDZ Planetary Climate Model

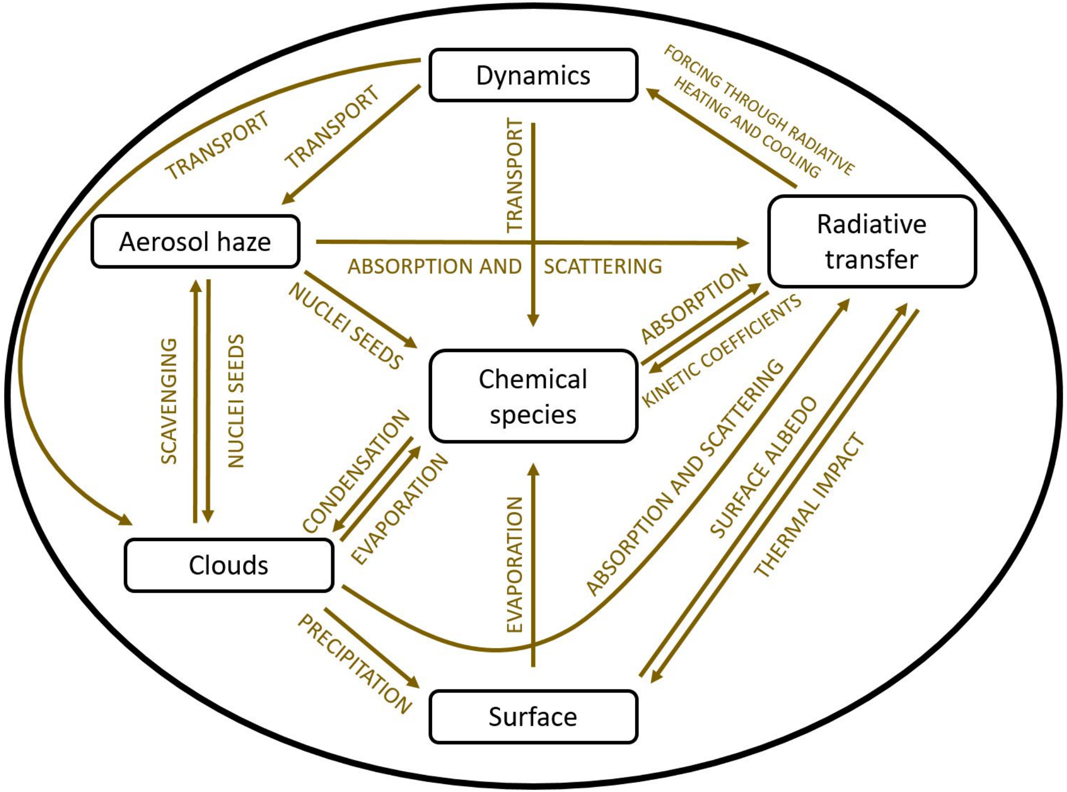
Highly coupled



Titan LMDZ Planetary Climate Model

Highly coupled

Radiative transfer: major impact on whole atmosphere

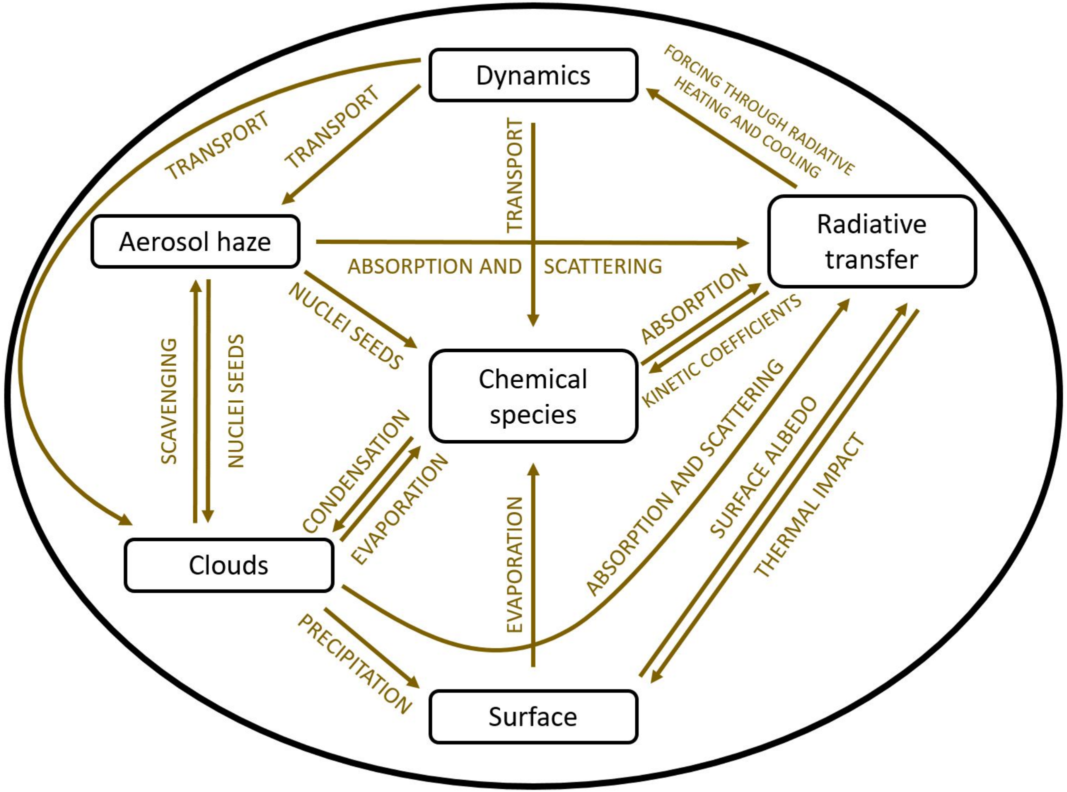


Titan LMDZ Planetary Climate Model

Highly coupled

Radiative transfer: major impact on whole atmosphere

Radiative transfer: 2-stream plane-parallel (McKay et al. 1989)



htrdr-planets: a nul-collision backward Monte Carlo radiative transfer model

htrdr-planets: model developed by Méso-Star (Toulouse, France)

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Monte Carlo radiative transfer: ray tracing

htrdr-planets: a nul-collision backward Monte Carlo radiative transfer model

htrdr-planets: model developed by Méso-Star (Toulouse, France)

Monte Carlo radiative transfer: ray tracing

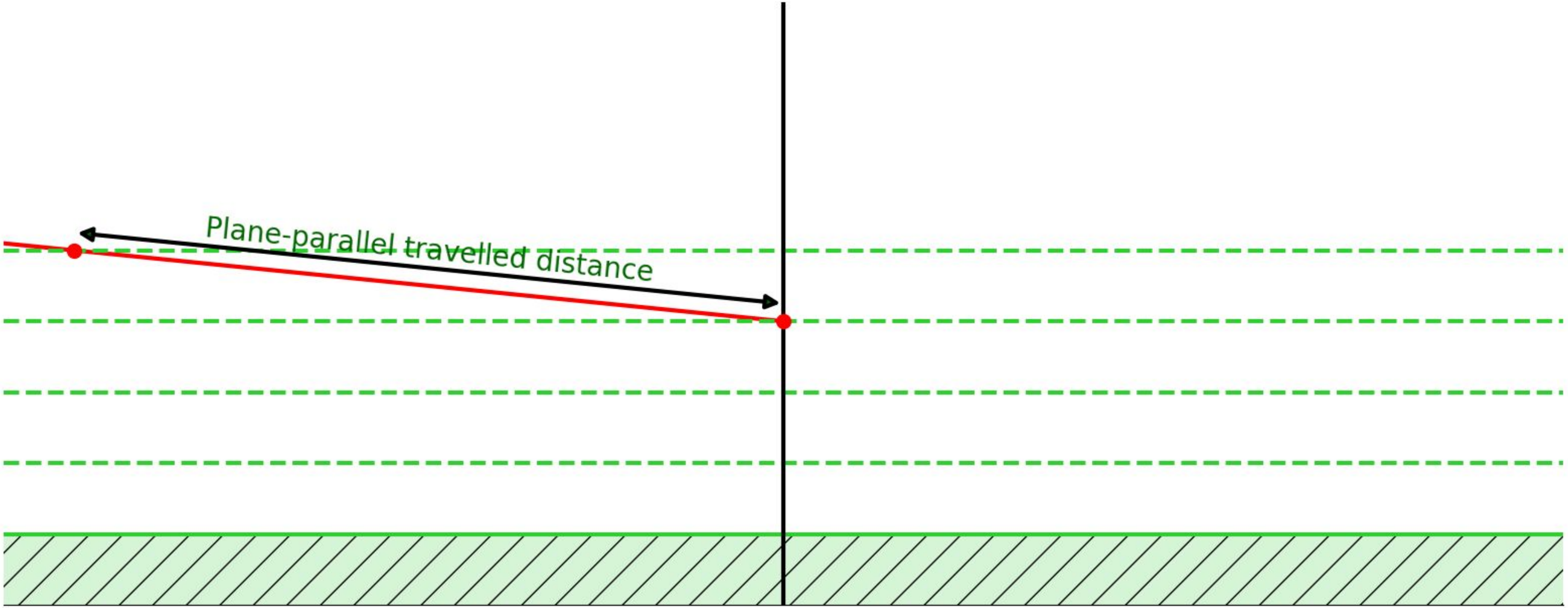
Works in complex geometries: account for sphericity effects

Fully heterogeneous model

Effects of sphericity

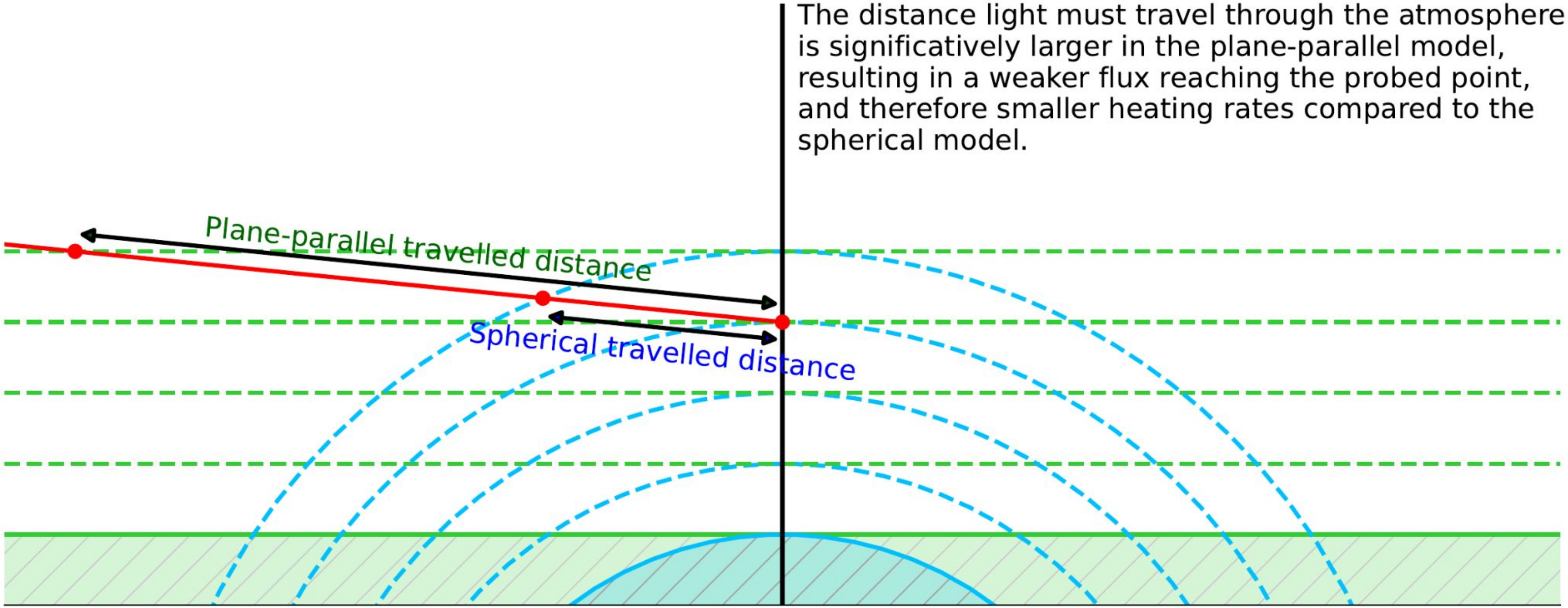
Terminator effects

plane-parallel: long travel distance ⇒ strong absorption



Terminator effects

plane-parallel: long travel distance ⇒ strong absorption
spherical: shorter travel distance ⇒ weaker absorption

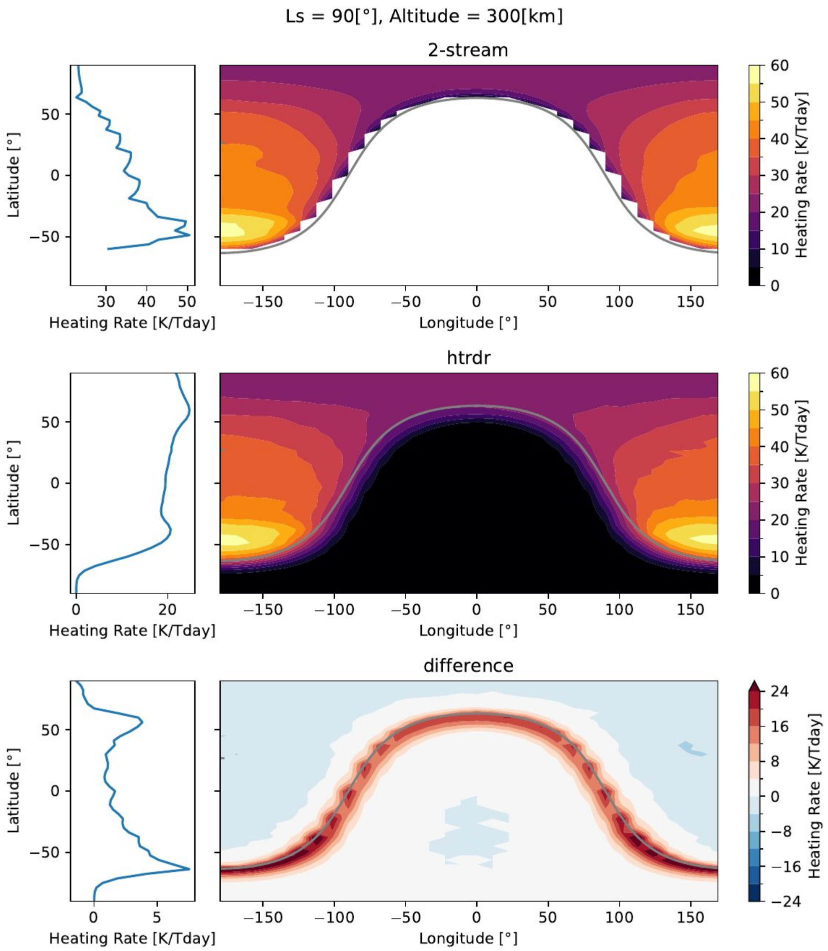


Terminator effects

plane-
parallel

htrdr
3D

differences



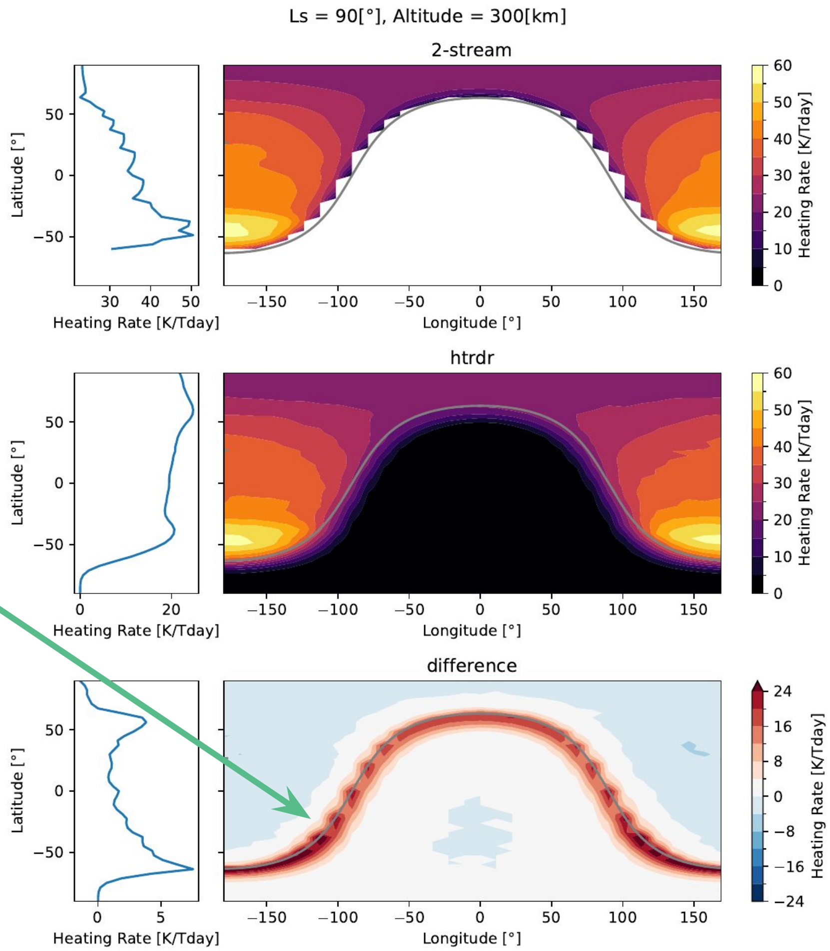
Terminator effects

Higher heating rates along the terminator

plane-parallel

htrdr 3D

differences



Terminator effects

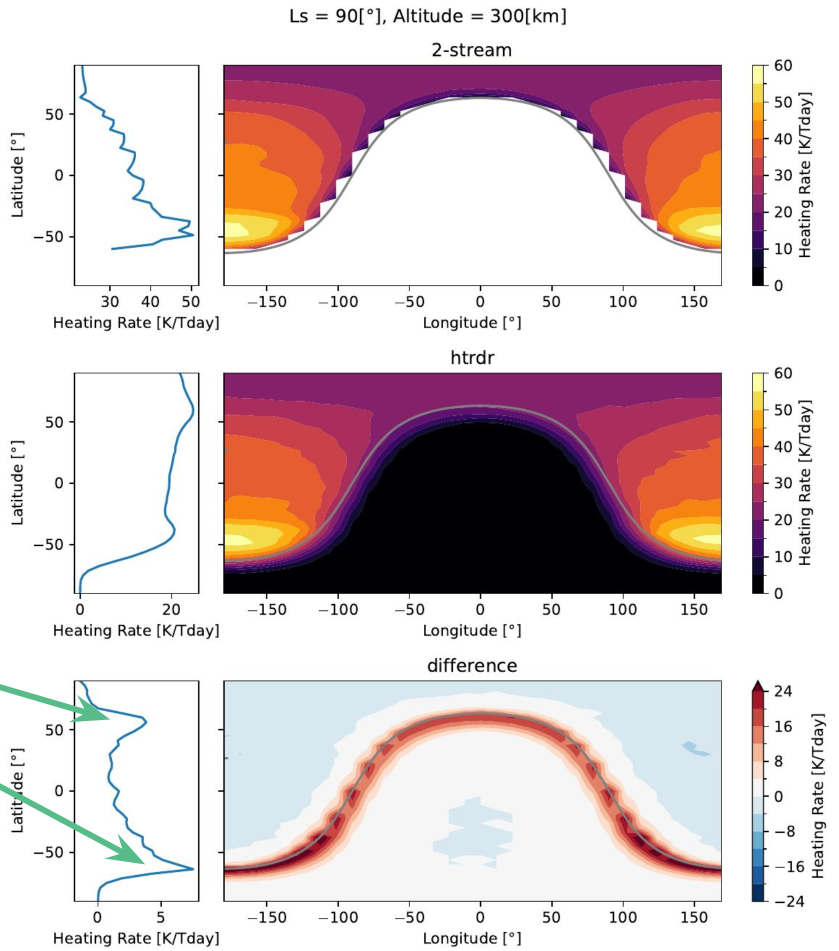
Higher heating rates along the terminator

Stronger effects near limits of polar night/day

plane-parallel

htrdr 3D

differences



Terminator effects

Higher heating rates along the terminator

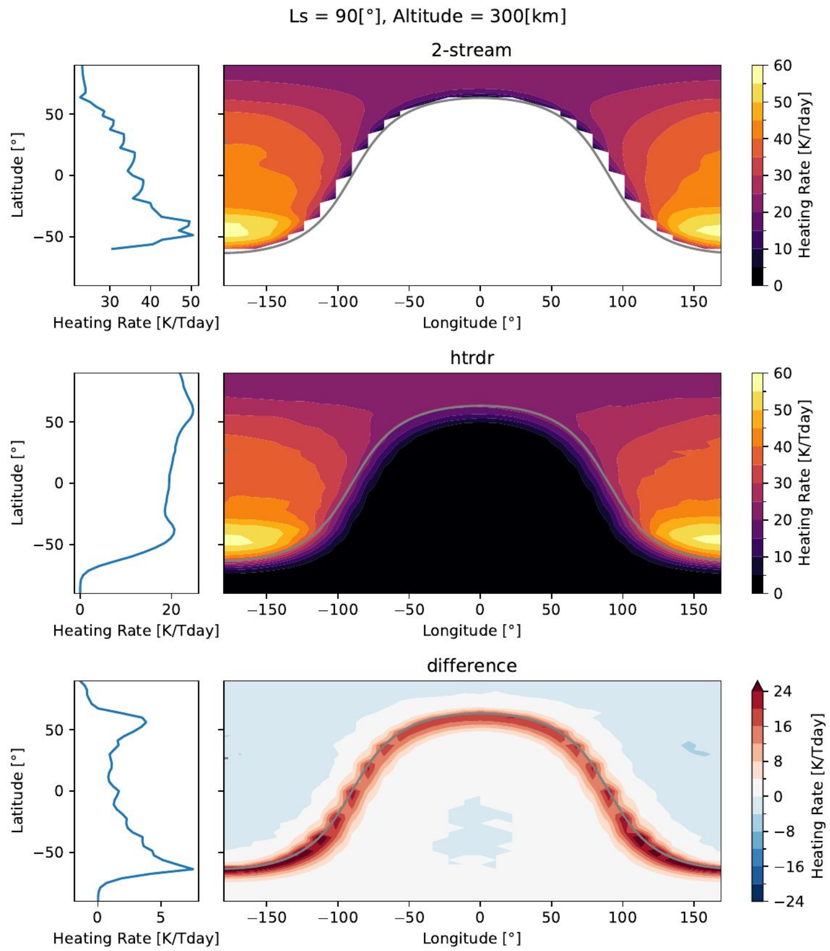
Stronger effects near limits of polar night/day

Zonal averaged differences around 5 K/Titan day

plane-parallel

htrdr 3D

differences



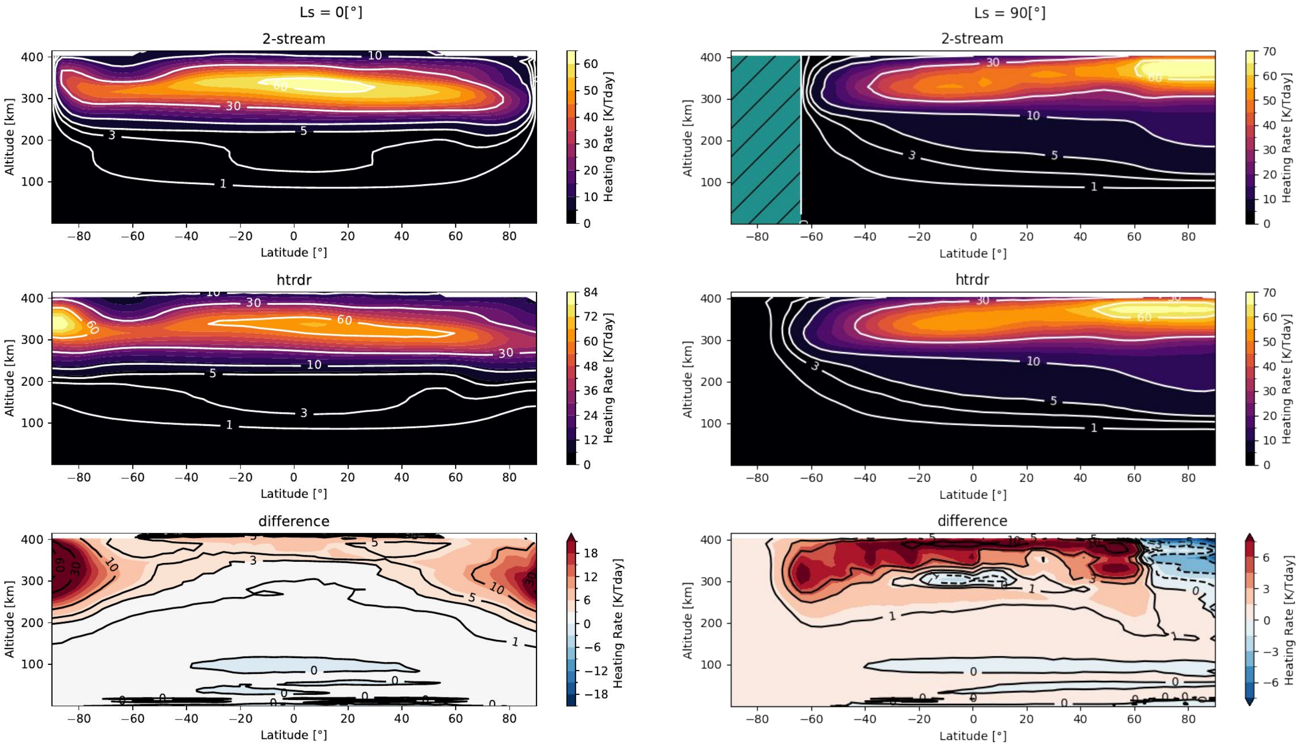
Equinoxe

Solstice

plane-parallel

htrdr 3D

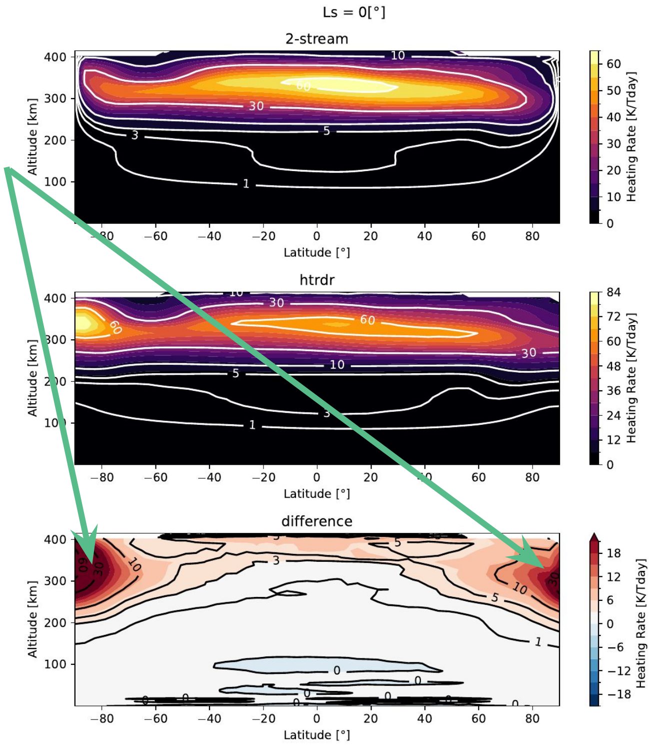
differences

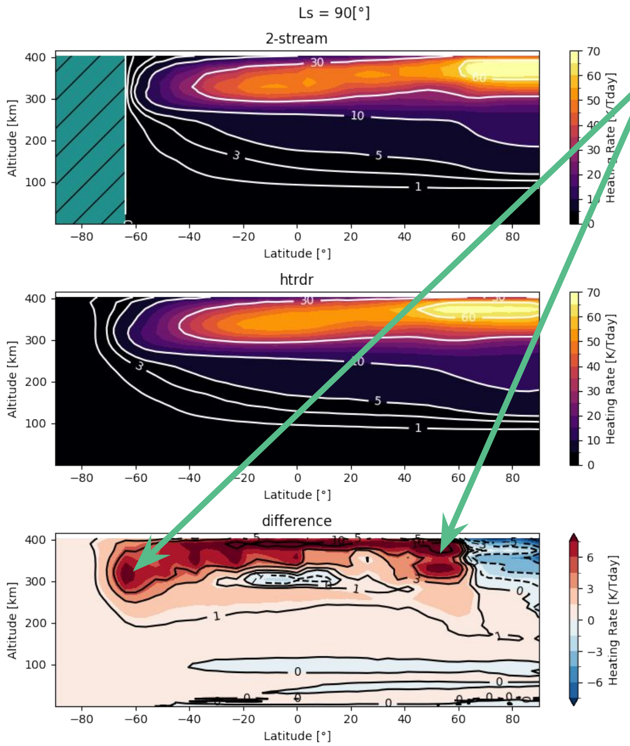


Equinoxes

Solstices

Main differences at the poles





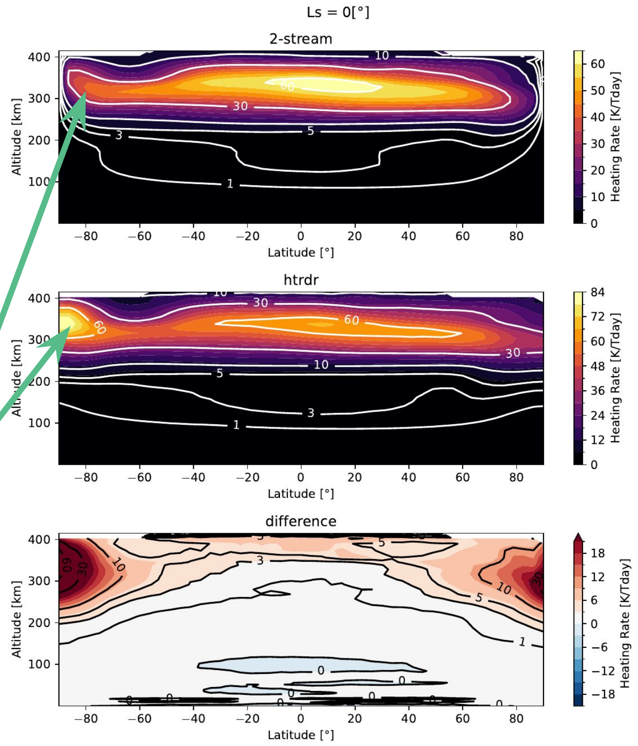
Main differences near 60° latitude: effect of terminator

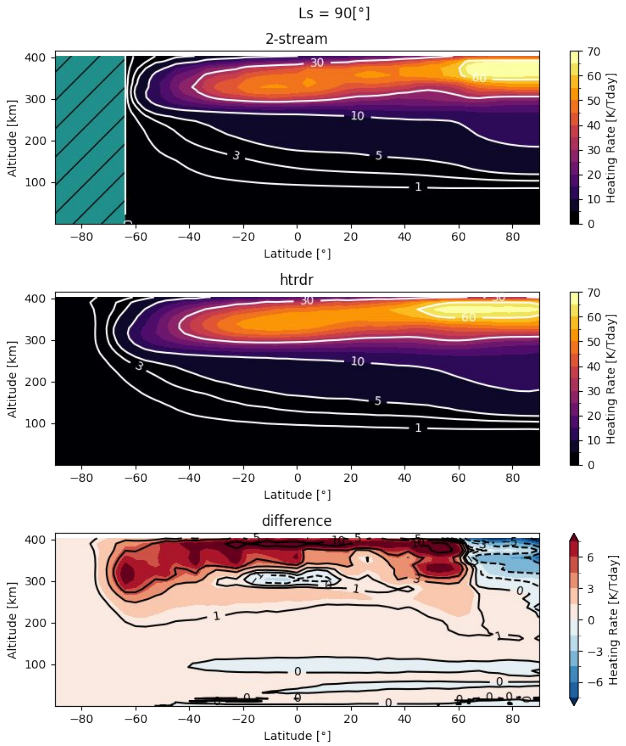
Equinoxes

Solstices

Main differences at the poles

Higher heating rates above former summer poles: detached haze layer at the limb





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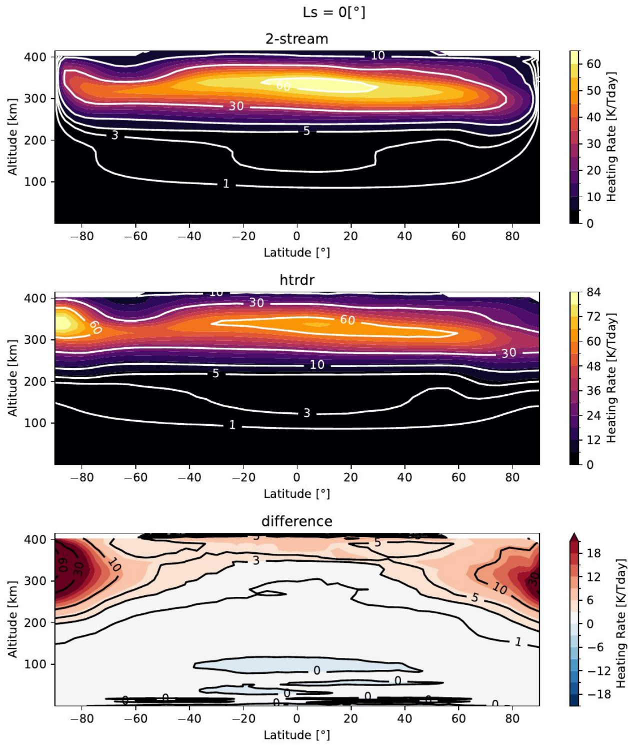
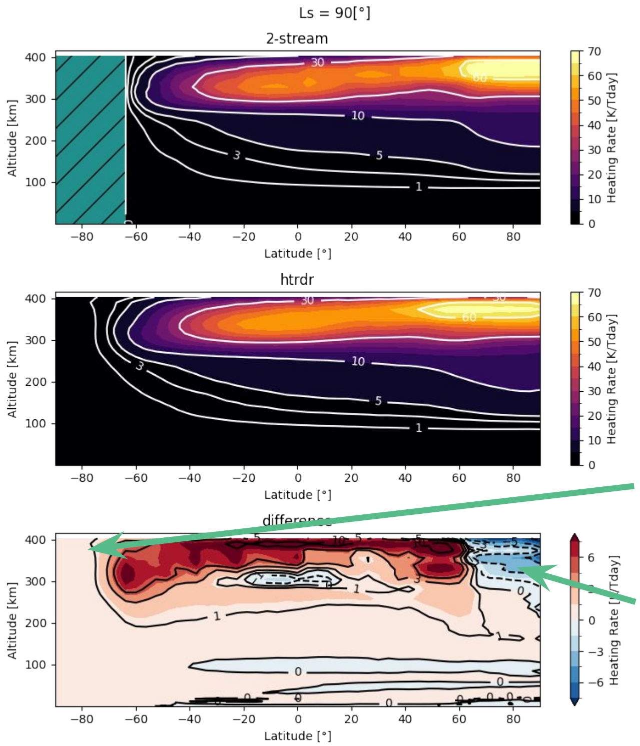


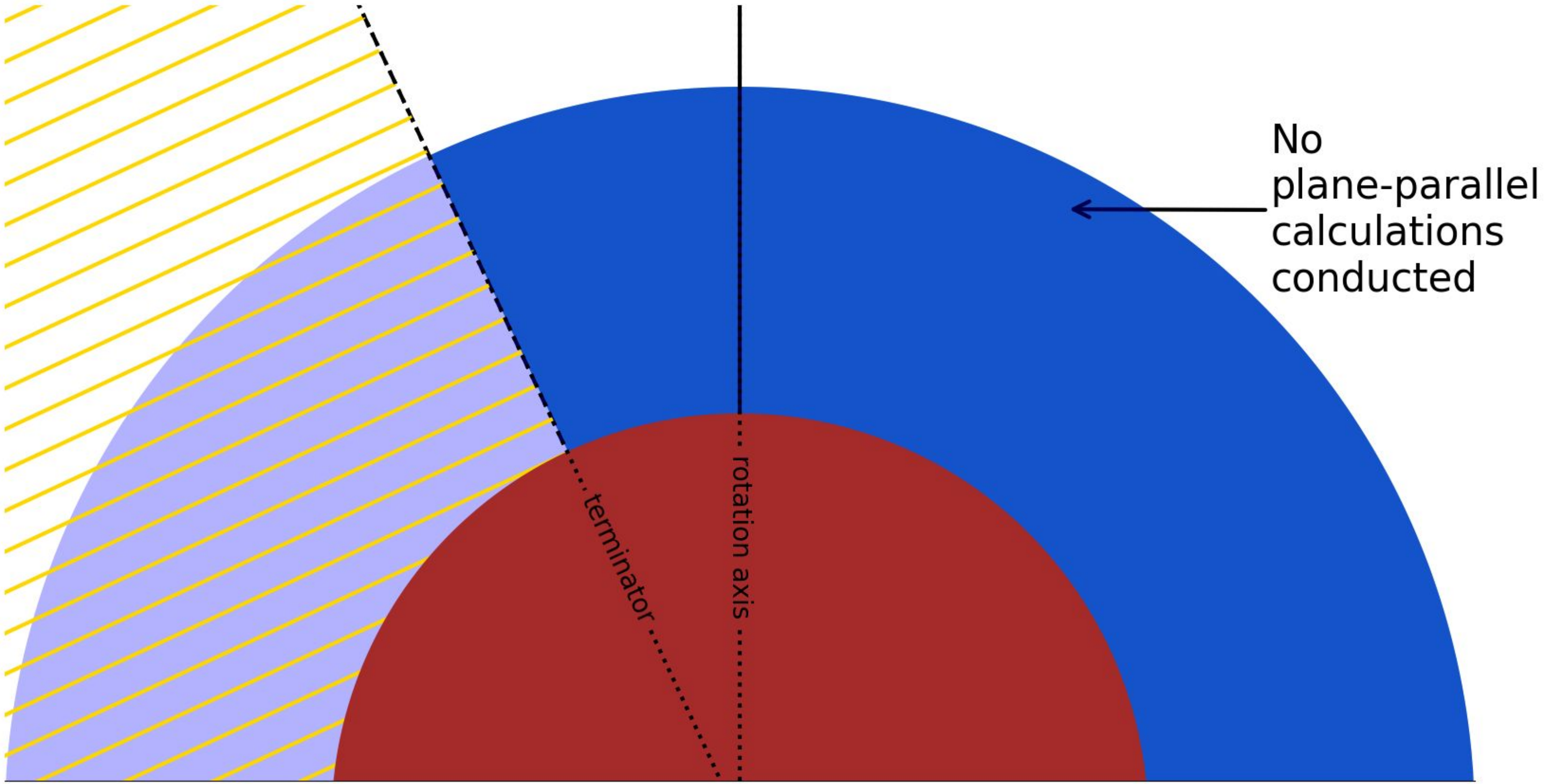


Main differences near 60° latitude: effect of terminator

Hotter polar night, cooler polar day

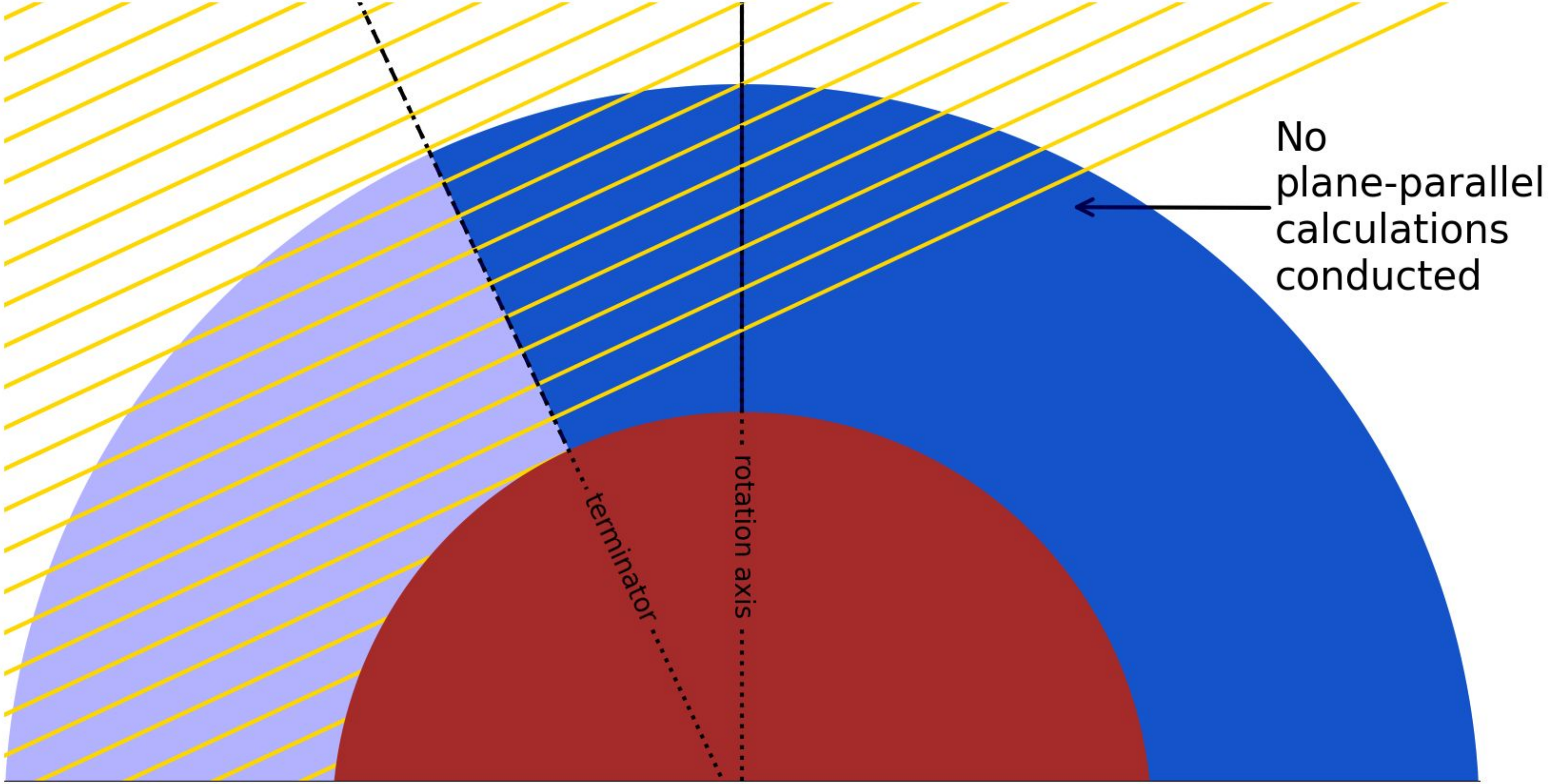
Effects on the polar regions

Plane-parallel



Effects on the polar regions

Spherical model

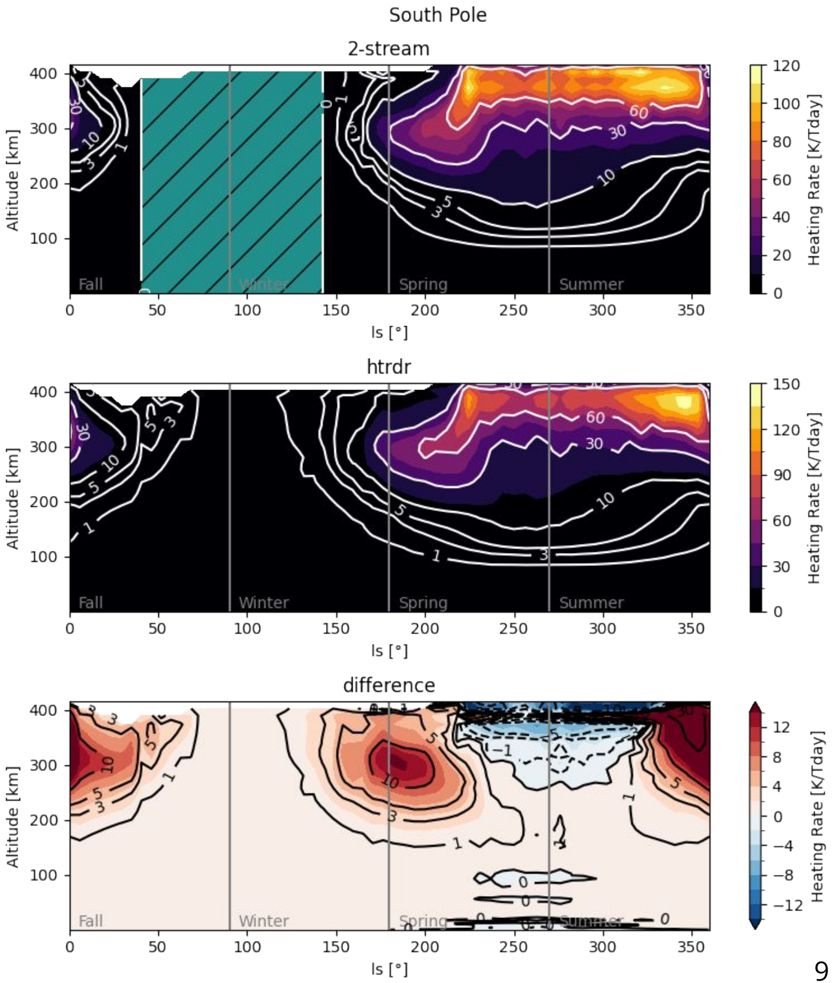


Effects on the polar regions

plane-
parallel

htrdr
3D

differences



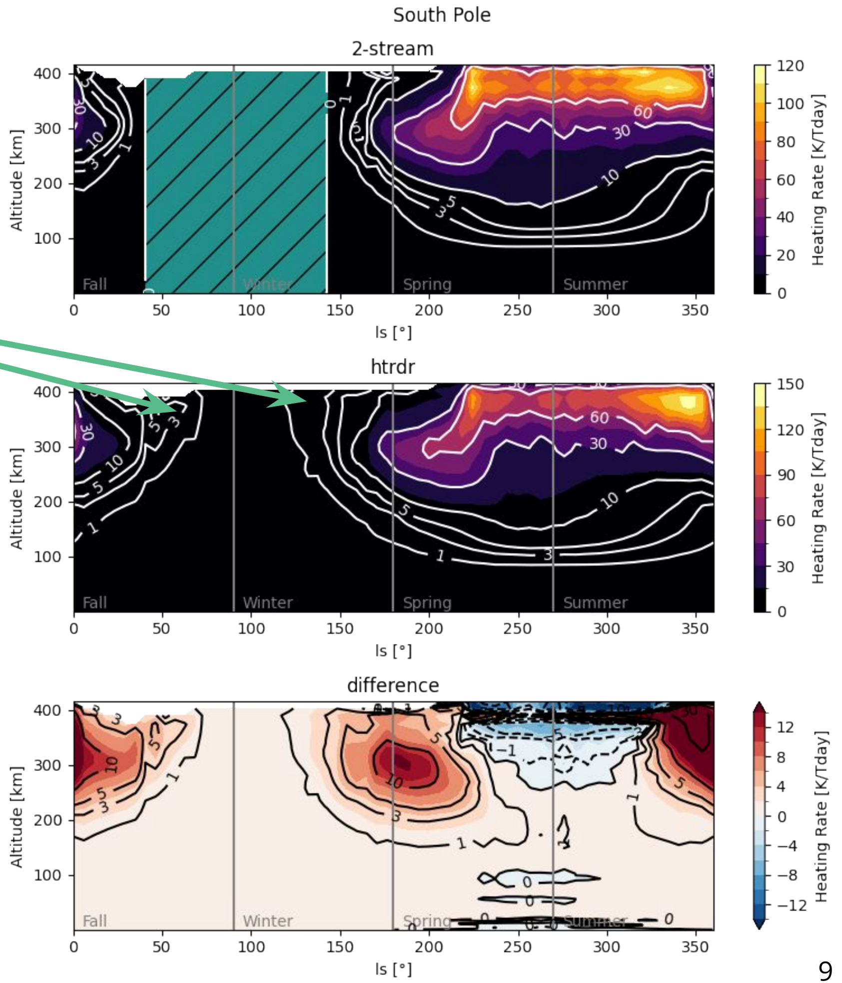
Effects on the polar regions

Heating rates in the polar region during winter

plane-parallel

htrdr 3D

differences



Effects on the polar regions

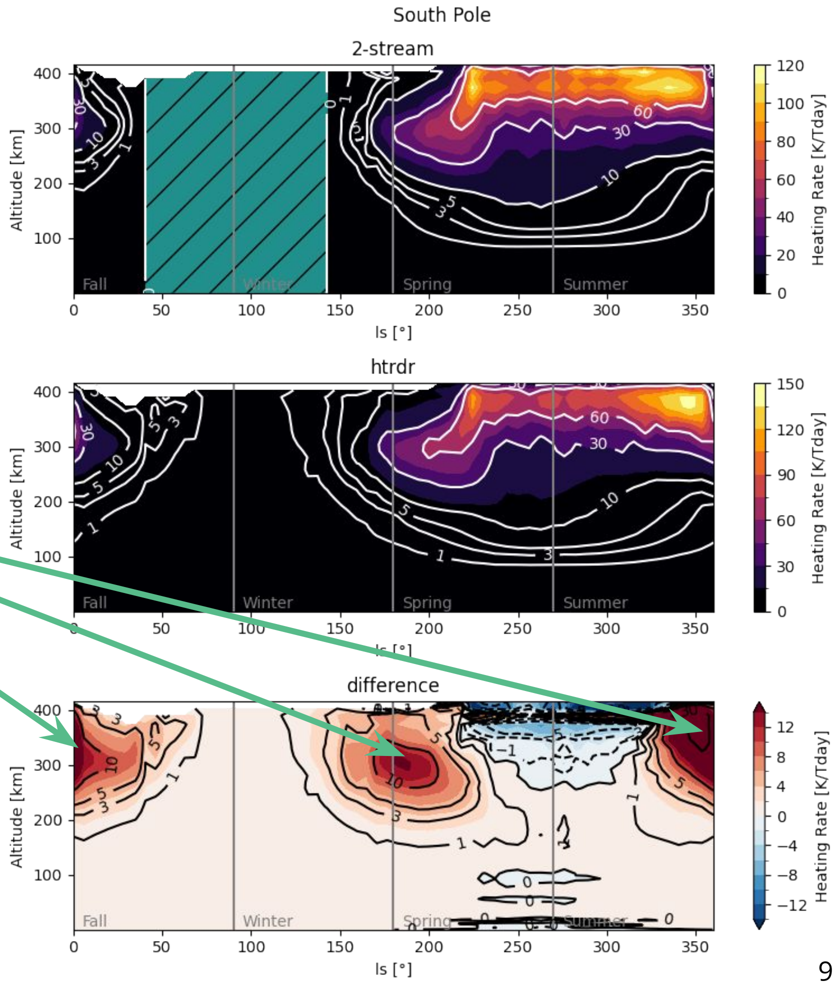
Heating rates in the polar region during winter

Main differences at equinox

plane-parallel

htrdr 3D

differences



Effects on the polar regions

Heating rates in the polar region during winter

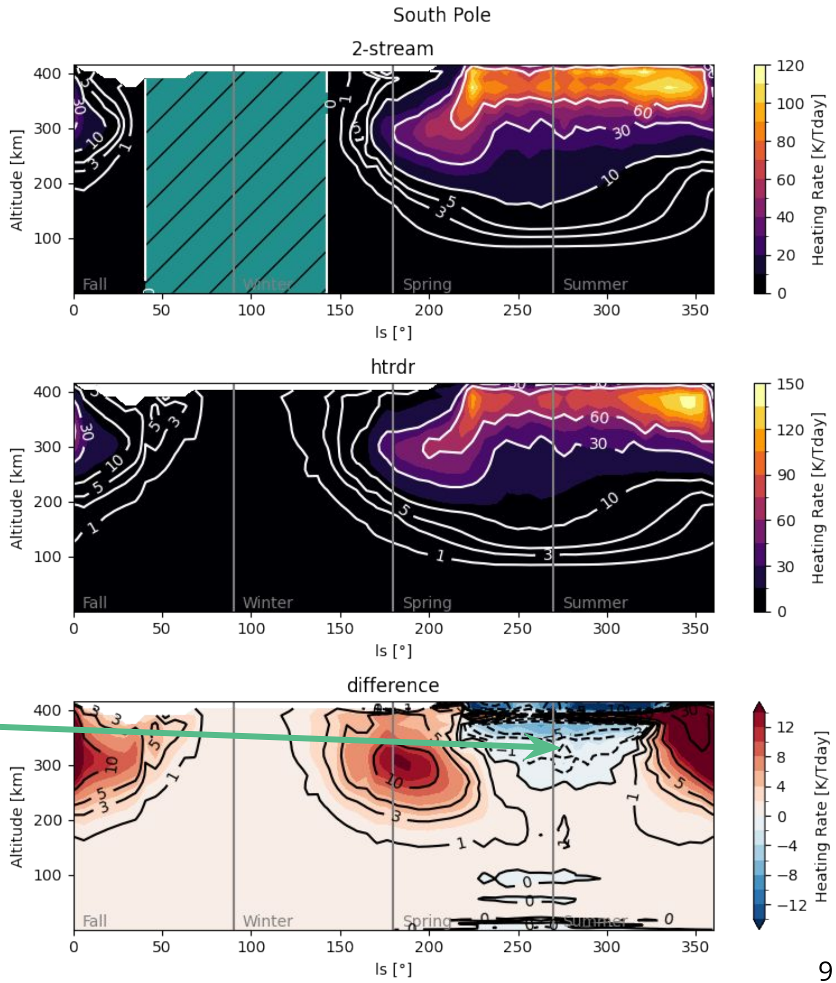
Main differences at equinox

Lower heating rates during spring/summer

plane-parallel

htrdr 3D

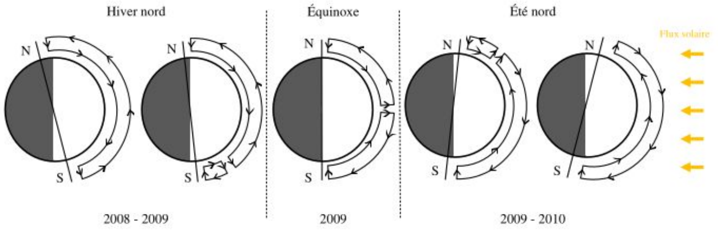
differences



Coupling with Titan LMDZ PCM

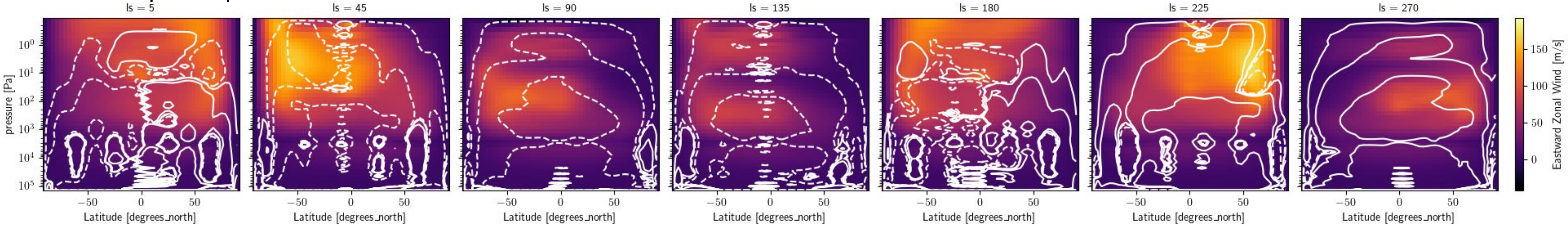
Preliminary results: circulation

Color Scale: zonal wind
White lines: meridional circulation
- Dotted: anti-clockwise rotation
- Solid: clockwise rotation

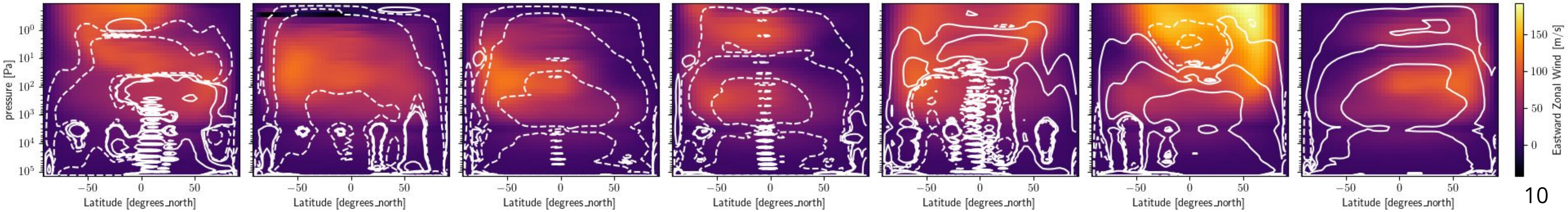


Northern spring **Northern summer** **Northern fall** **Northern winter**

Reference (plane-parallel)



Coupled (3D radiative transfer)



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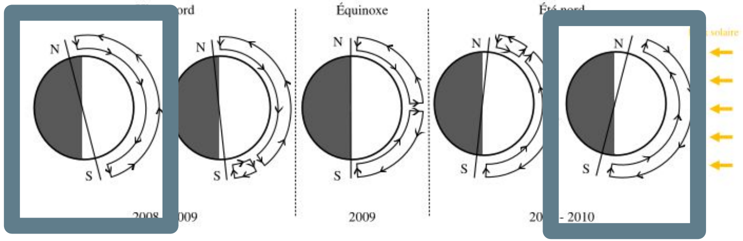
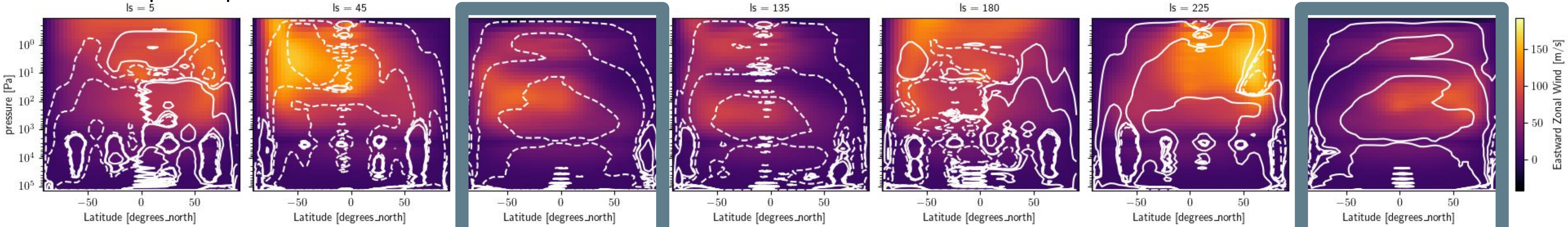


Color Scale: zonal wind
White lines: meridional circulation
Dotted: anti-clockwise rotation
Solid: clockwise rotation

Northern spring
Northern summer
Northern fall
Northern winter

Reference (plane-parallel)



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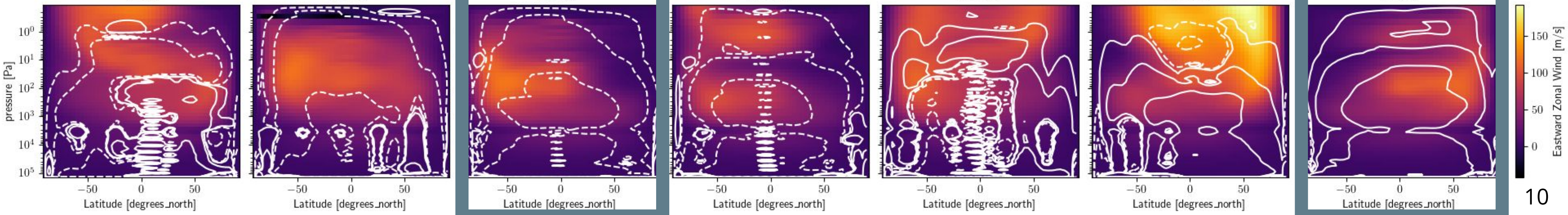
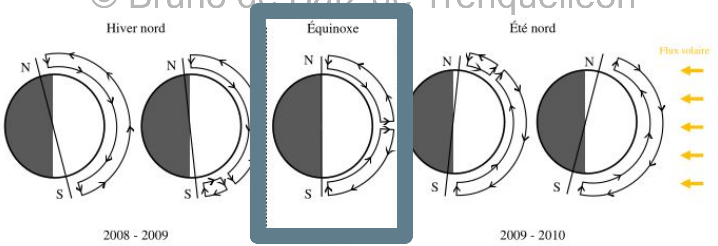


Preliminary results: circulation



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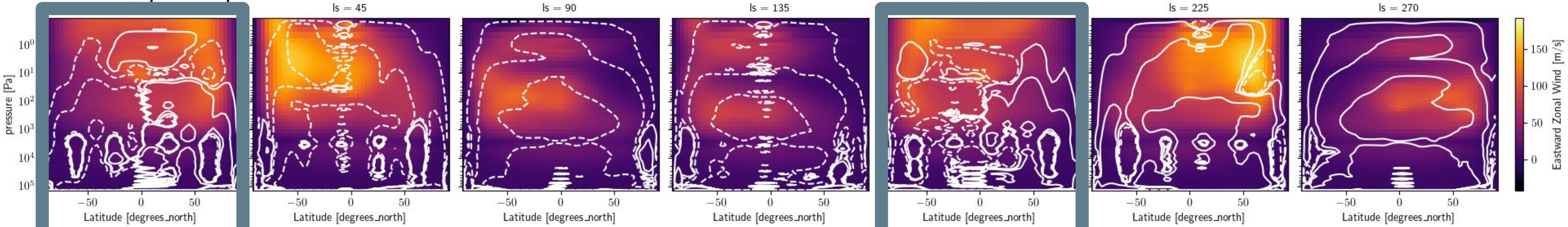
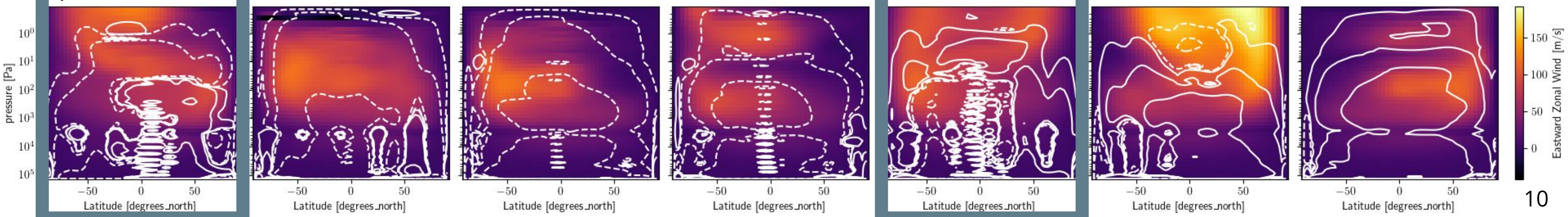
Northern spring Northern summer Northern fall Northern winter

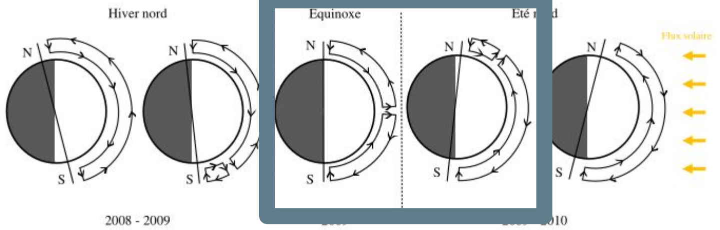
Reference (plane-parallel)



Coupled (3D radiative transfer)



Preliminary results: circulation



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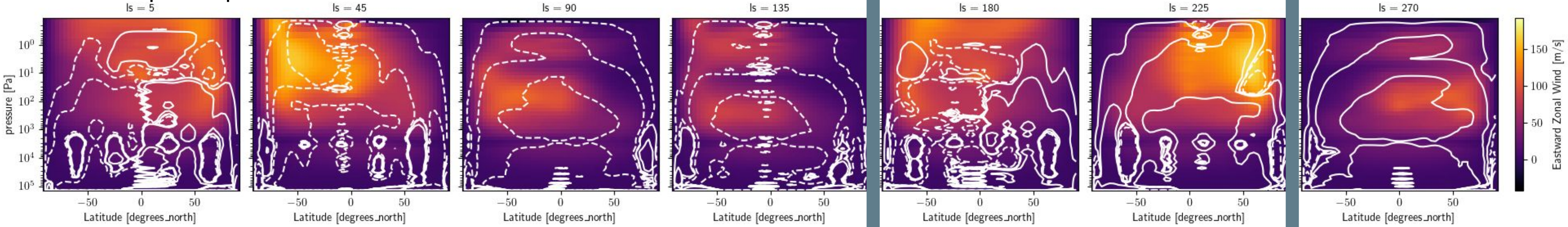

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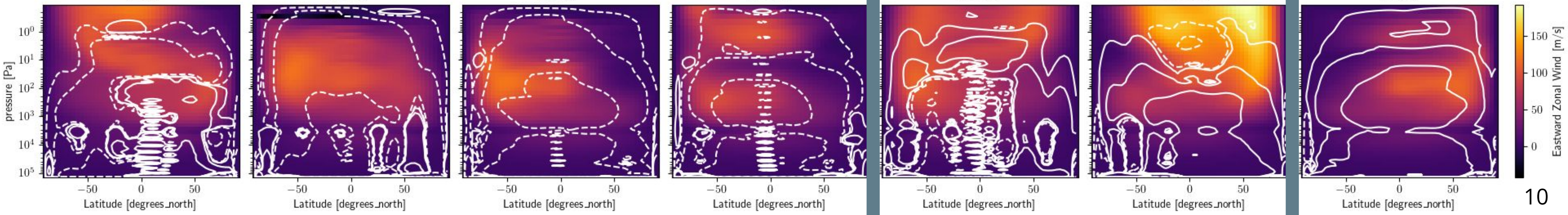
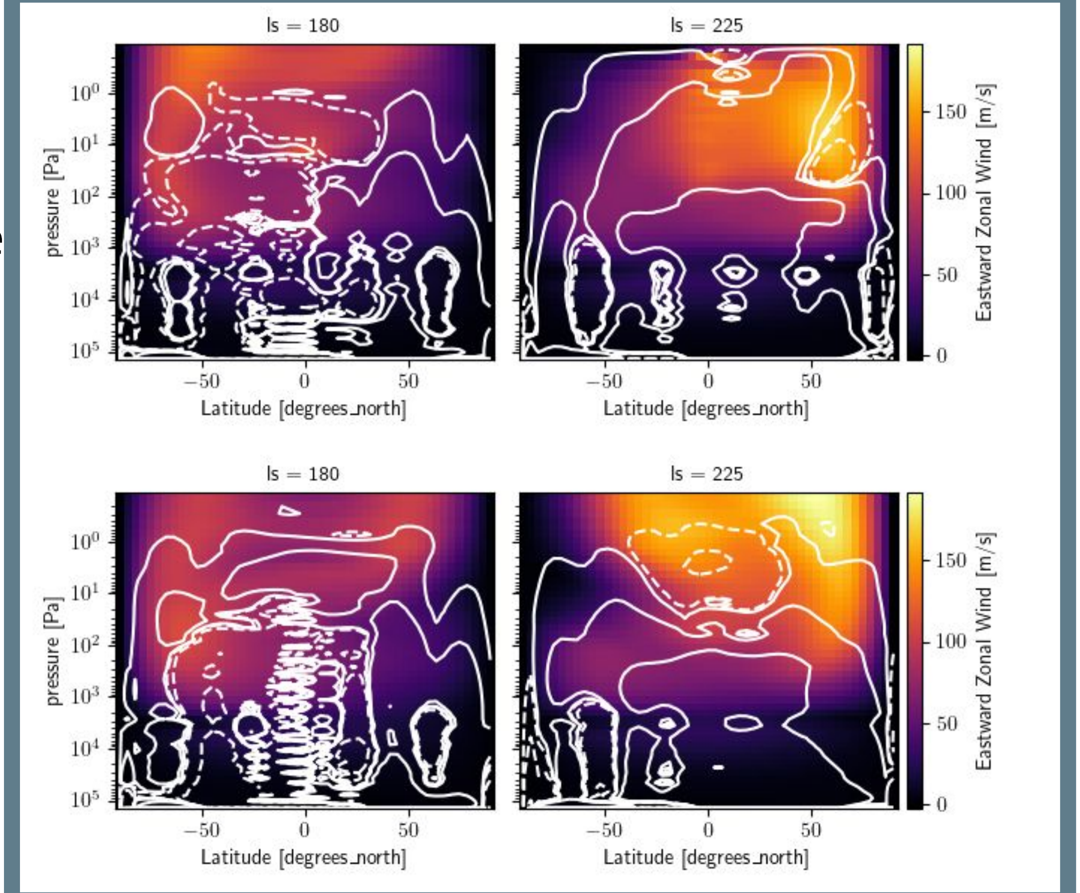
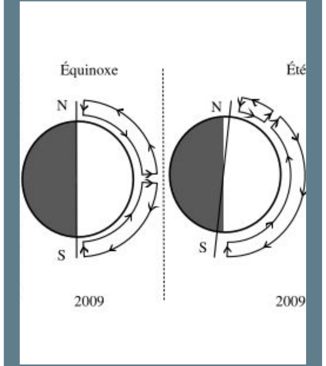


Preliminary results: circulation

Reference (plane-parallel)

Coupled (3D radiative transfer)





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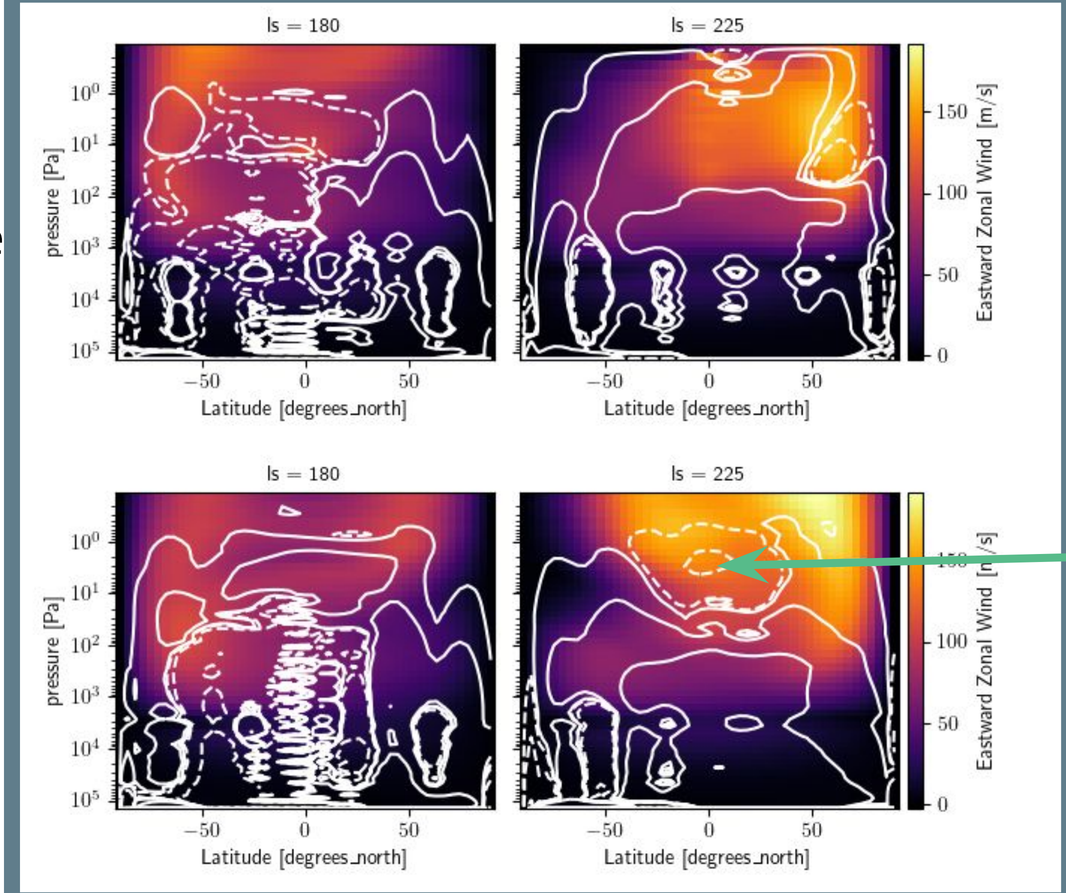
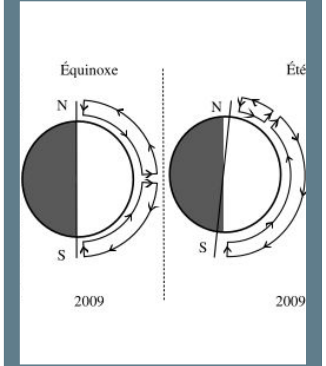
Reference (plane-parallel)

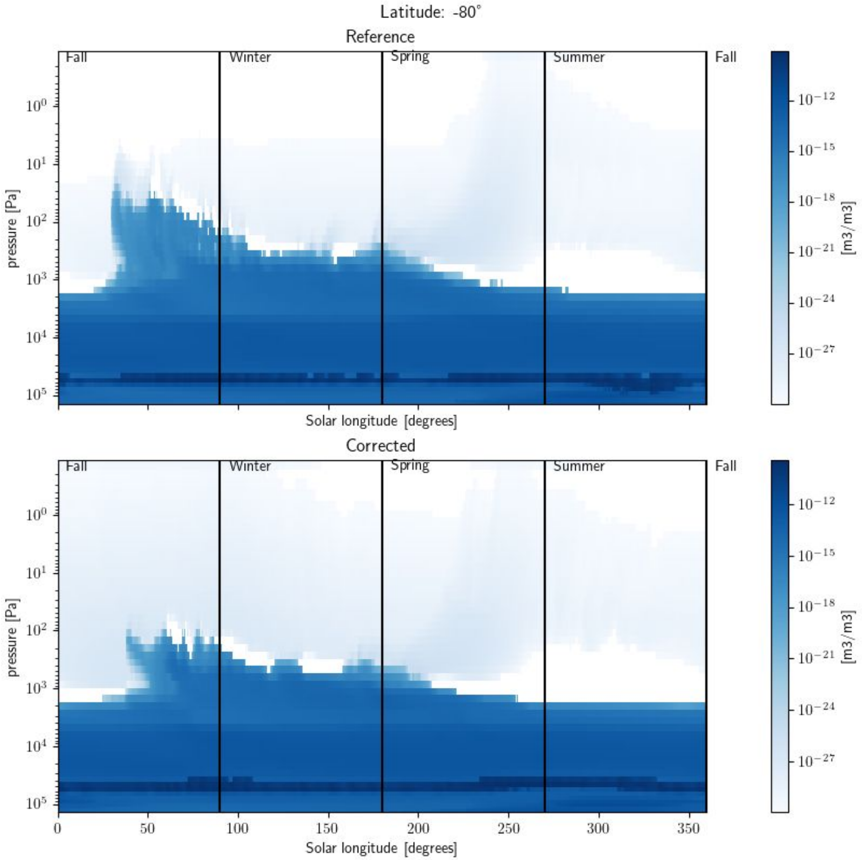
Coupled (3D radiative transfer)





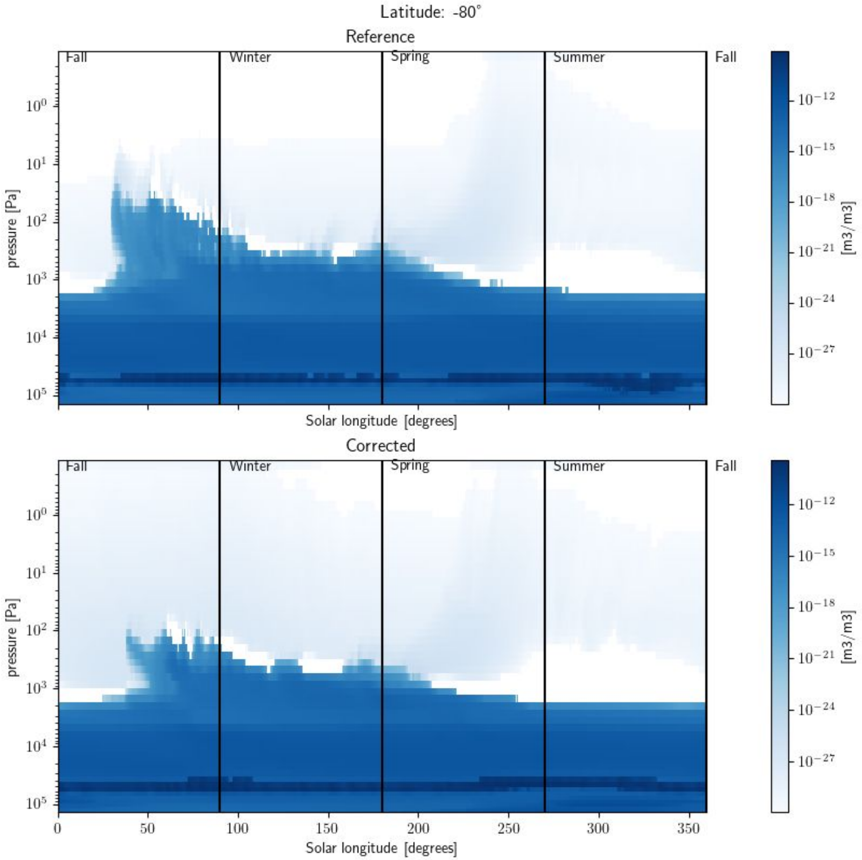
Additional cells in upper stratosphere after the equinox

Preliminary results: polar cloud



Preliminary results: polar cloud

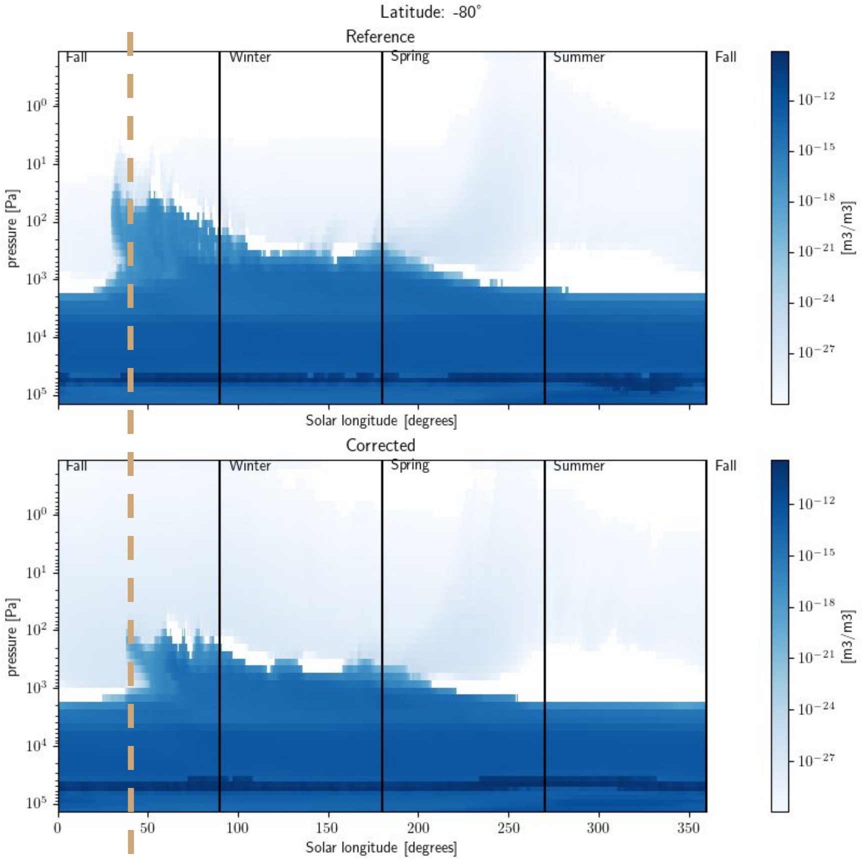
Heating of the upper layer of the polar region during winter:



Preliminary results: polar cloud

Heating of the upper layer of the polar region during winter:

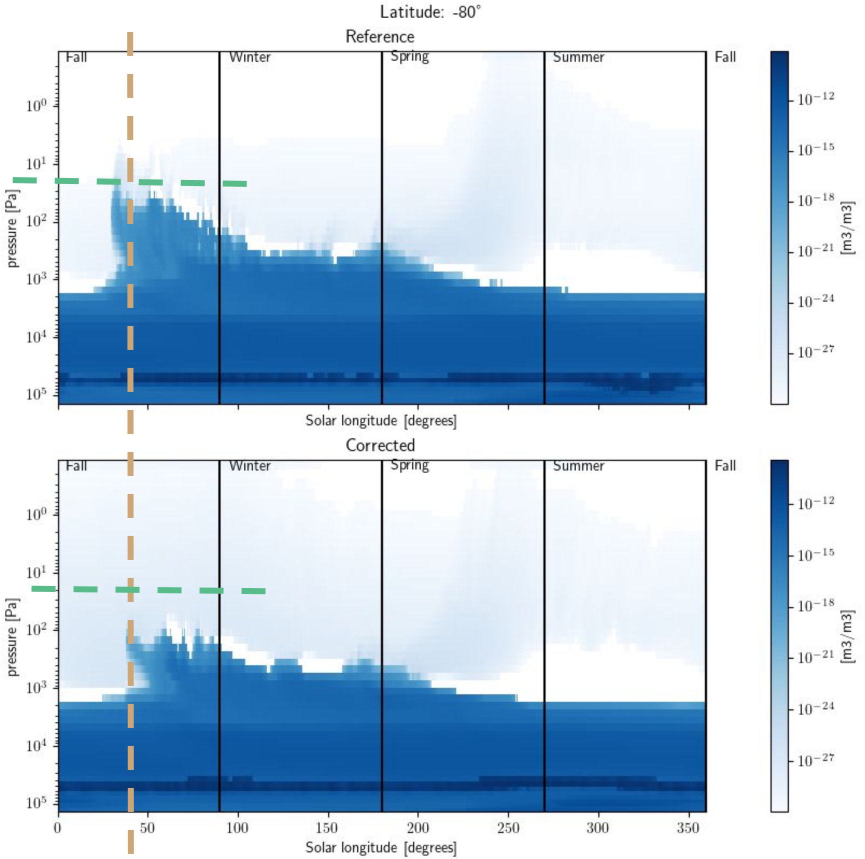
- Polar cloud forms later



Preliminary results: polar cloud

Heating of the upper layer of the polar region during winter:

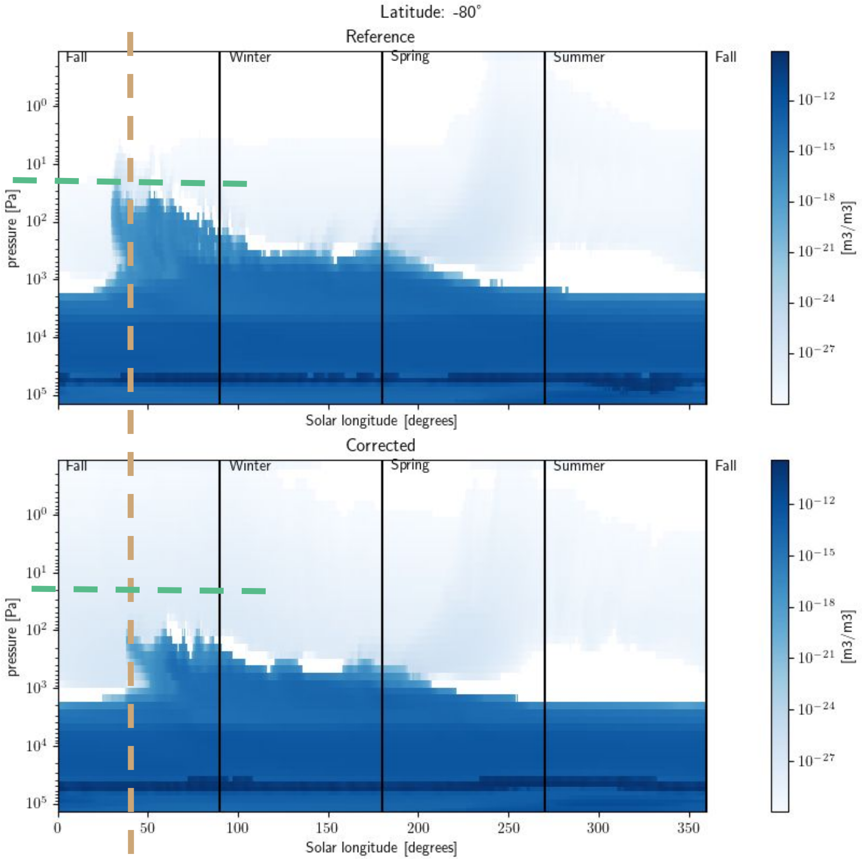
- Polar cloud forms later
- Starts at lower altitudes



Preliminary results: polar cloud

Heating of the upper layer of the polar region during winter:

- Polar cloud forms later
- Starts at lower altitudes
- Does not match observations anymore...



Takeaways:

I am looking for a postdoc

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- Major effects along terminator and polar regions

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⇒ Is Titan flat after all?

Takeaways:

I am looking for a postdoc

- Major effects along terminator and polar regions
- Modify/delay dynamics
- Impede the formation of the polar cloud

  ⇒ Is Titan flat after all?

No! Just need some tuning...

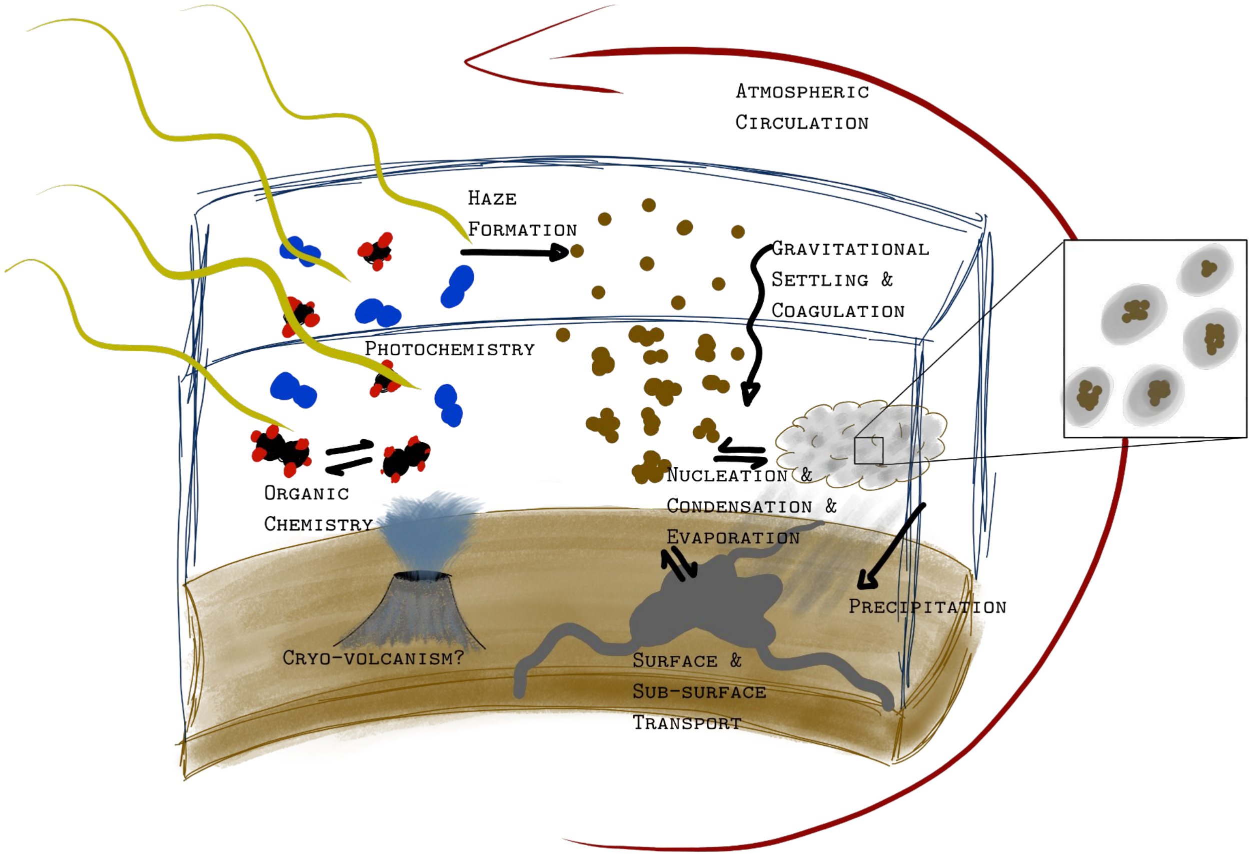
Thank you!

p.s. I am still looking for a postdoc ...

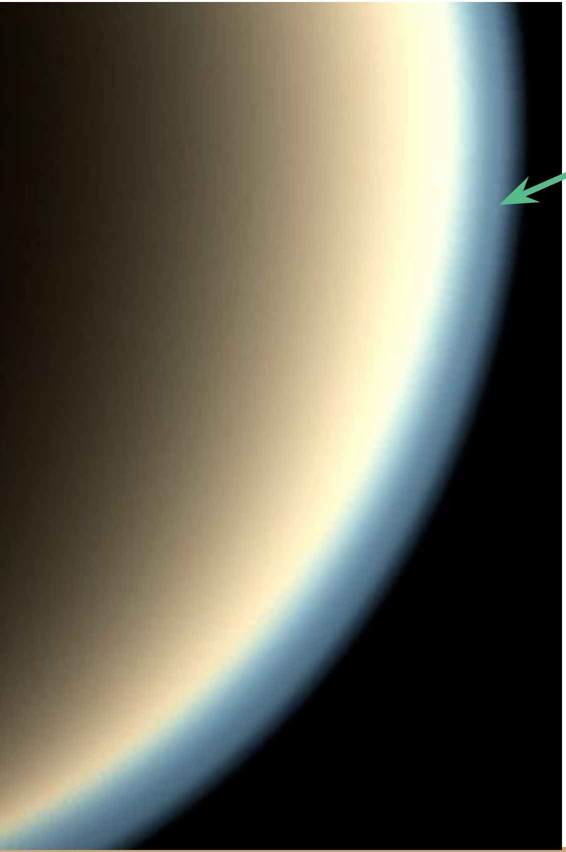
This work has been funded by the ~~Flat Titan Society~~ ANR RaD^3-net

Titan in a nutshell

- Organic chemistry
- Photochemistry
- Haze & Cloud microphysics
- HCN below the tropopause
- CH4 clouds deeper
- Surface / Atmosphere exchange



Titan main features



Detached haze layer

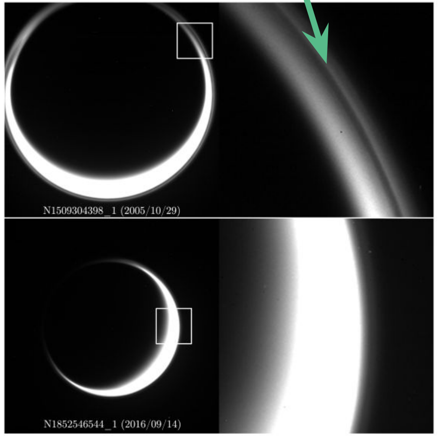


Figure S3: High phase angle images of the main and detached hazes of Titan before the collapse of the detached haze (top) and at the time of the reappearance (bottom). The observations are quite similar in terms of geometry with 155° and 142° phase angle for the 2005 and 2016 images. Images on the right half of the figure show the equatorial region corresponding to the squares in the left half.

West et al. (2018)

West et al. (2016)

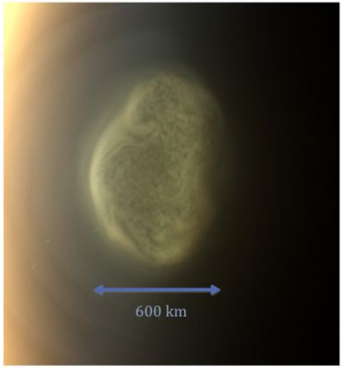
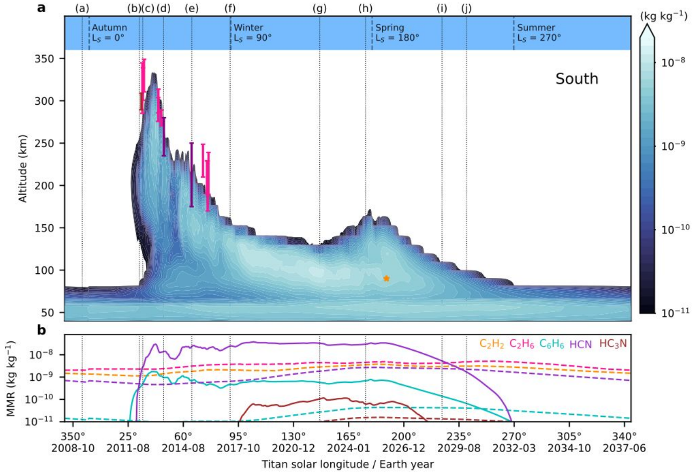


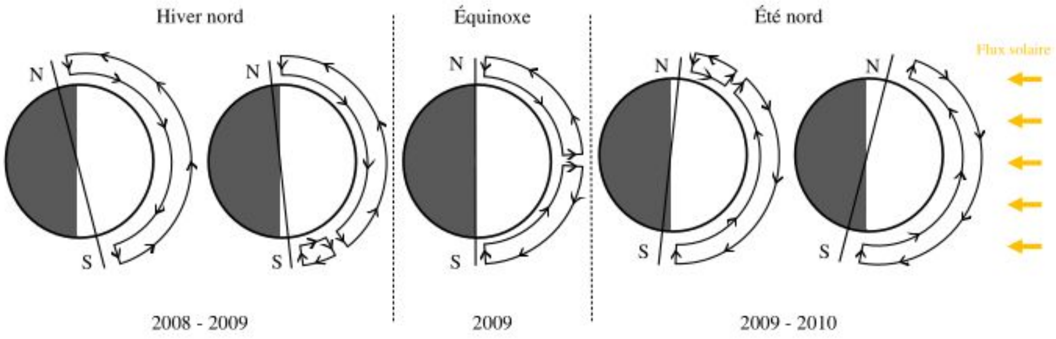
Fig. 6. This image taken on 2012-178 (26 June) shows a previously unseen cloud patch near Titan's south pole. Solar illumination is from the left. This color image was constructed from images N1719446170 (red), N1719446086 (green) and N1719446000 (blue).

Polar cloud



de Batz de Trenquelléon et al. (2026)

Titan dynamics



(Bruno De Batz de Tranquelléon 2024)

Super-rotation of the stratosphere

At solstices: A single Hadley cell from

Upwelling at summer pole, Downwelling at winter pole

During winter / summer: inversion of the circulation (split in 2 cells)

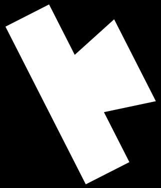
At equinoxes: 2 cells

Upwelling at equator, Downwelling at the poles

Source

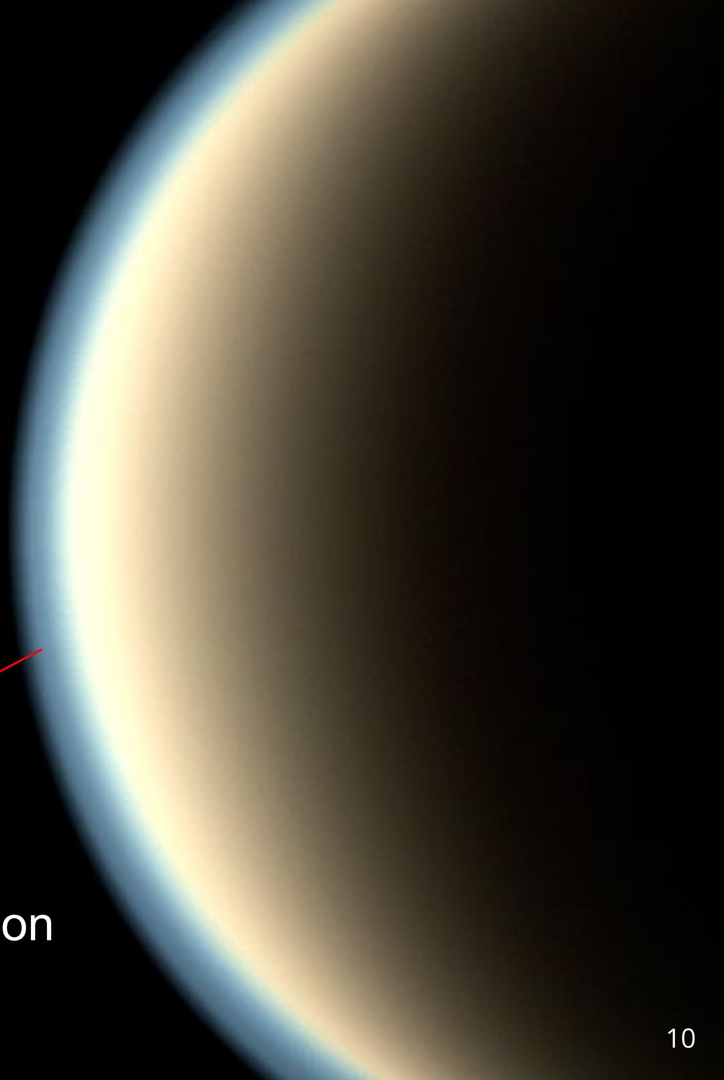
Ray tracing procedure

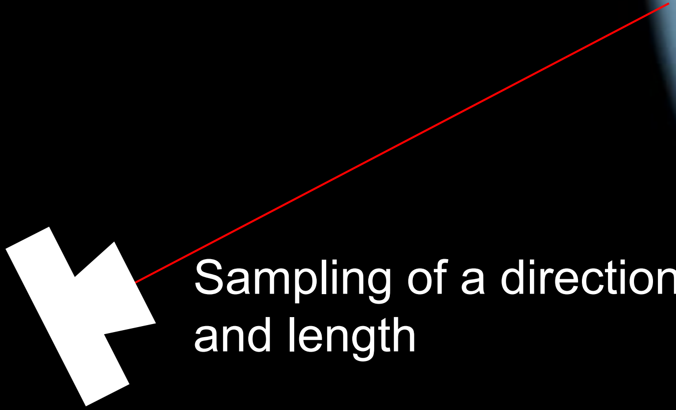
w = 0



Source

Ray tracing procedure





Source

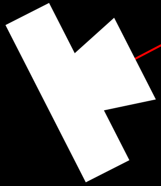
Ray tracing procedure

On Event:

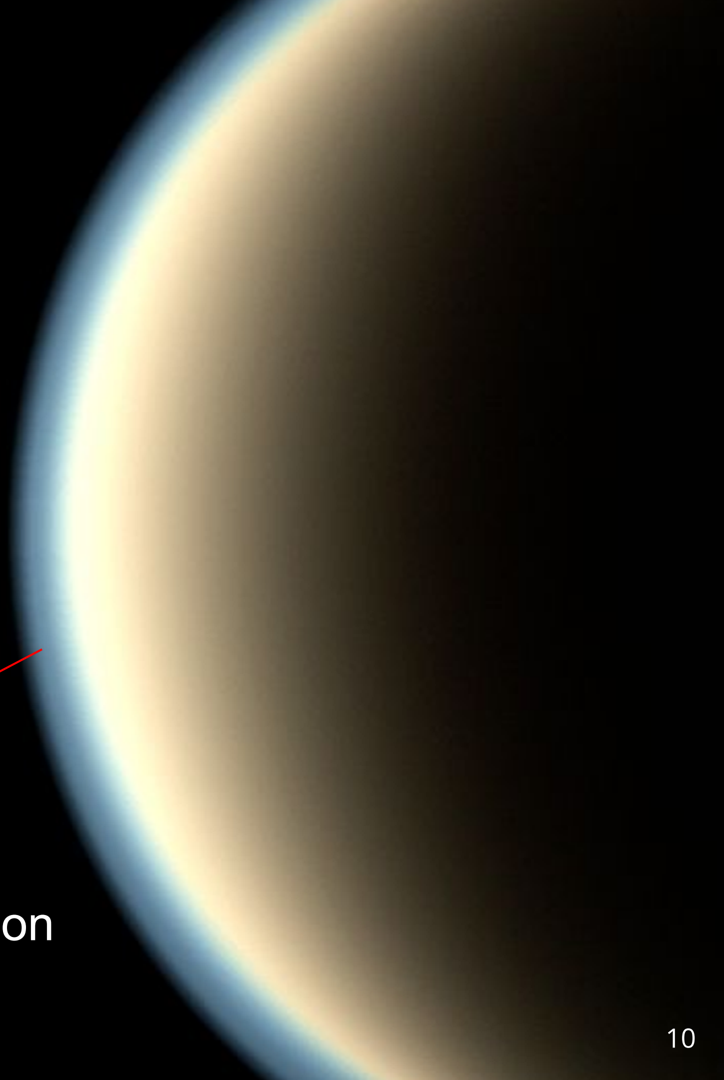
- scattering ($p=k_s/k_{ext}$)

- absorption ($p=k_a/k_{ext}$)

w = 0



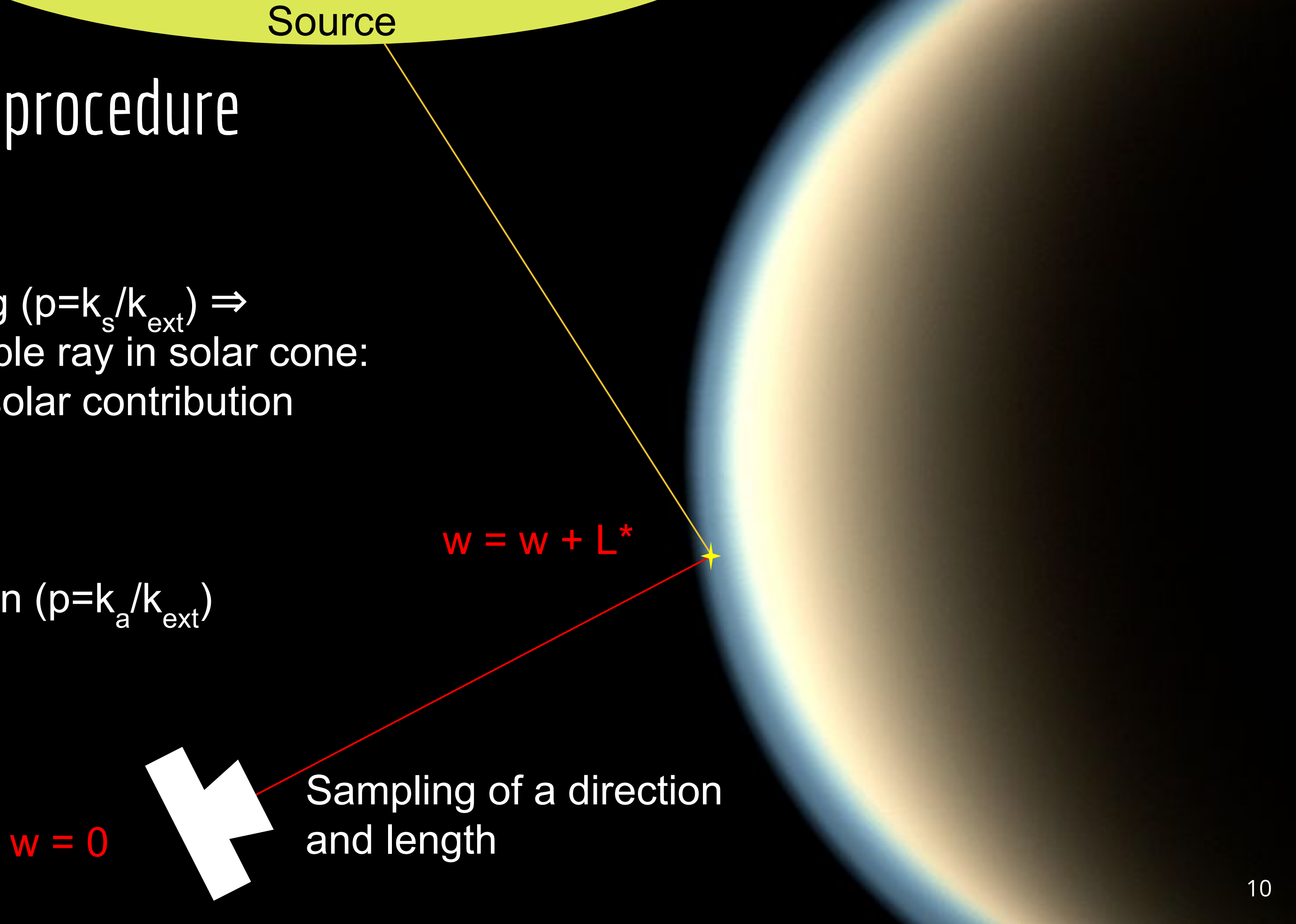
Sampling of a direction and length



Ray tracing procedure

On Event:

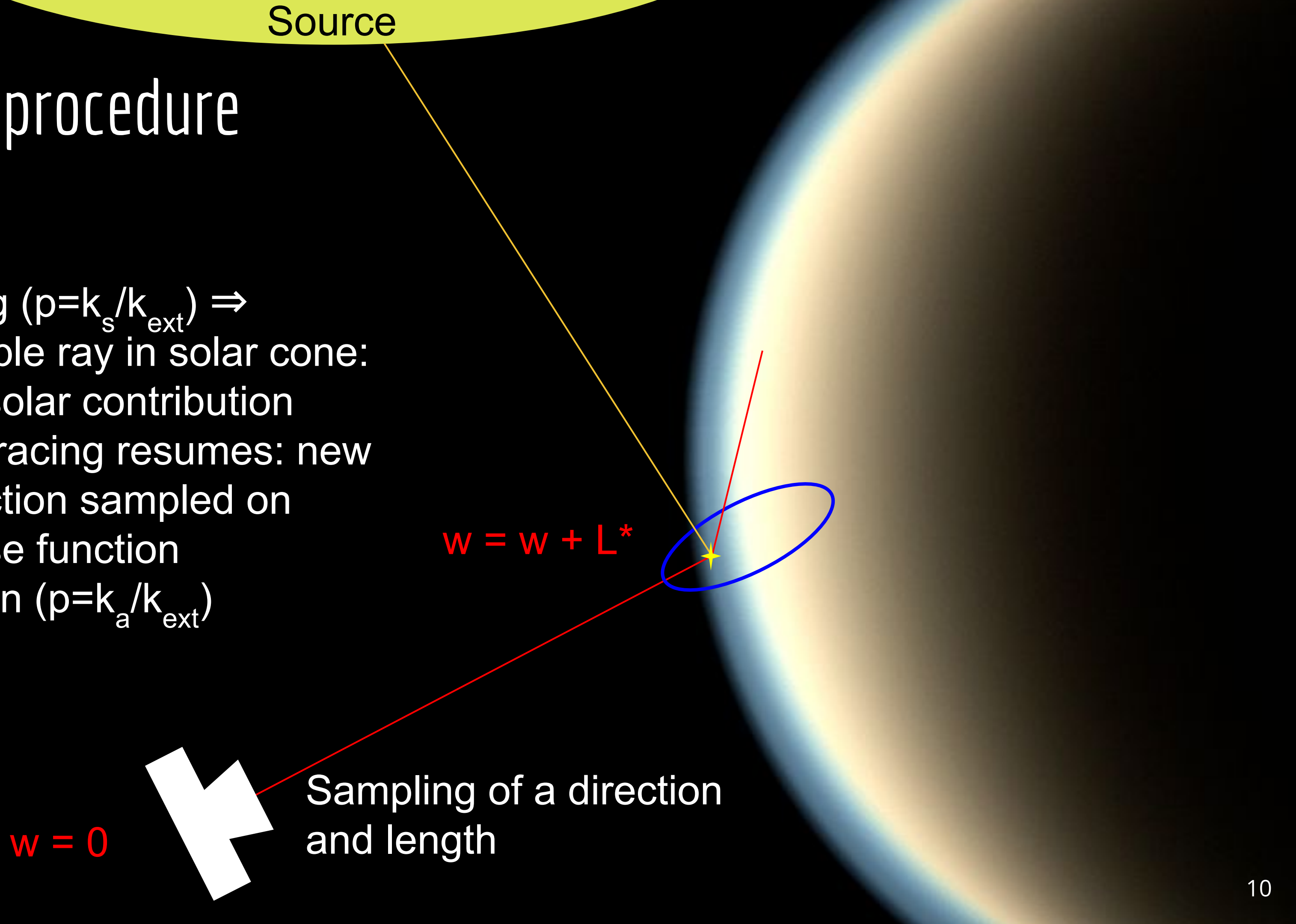
- scattering ($p=k_s/k_{ext}$) ⇒
  - sample ray in solar cone: get solar contribution
- absorption ($p=k_a/k_{ext}$)



Ray tracing procedure

On Event:

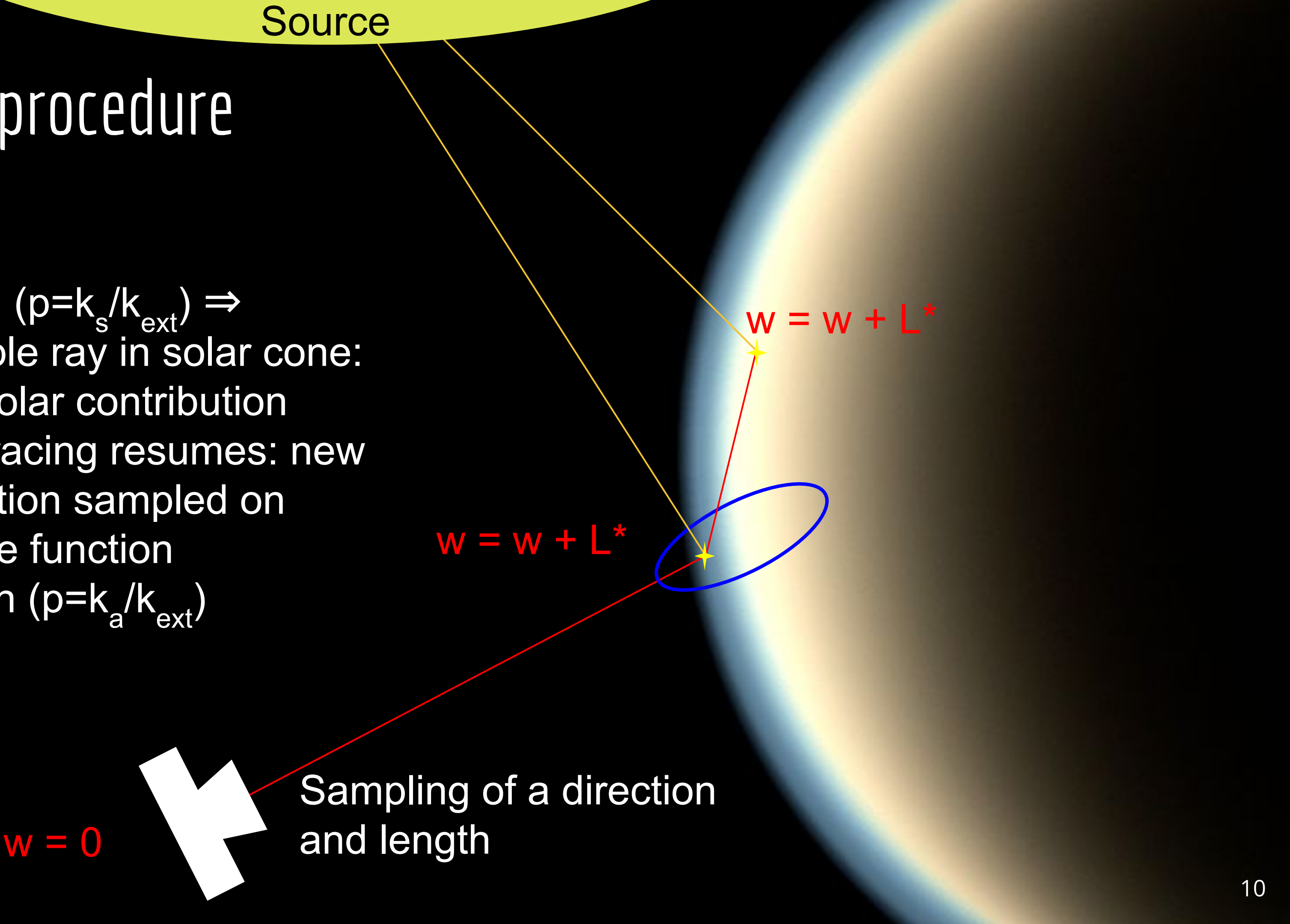
- scattering ($p=k_s/k_{ext}$) ⇒
  - sample ray in solar cone: get solar contribution
  - ray tracing resumes: new direction sampled on phase function
- absorption ($p=k_a/k_{ext}$)



Ray tracing procedure

On Event:

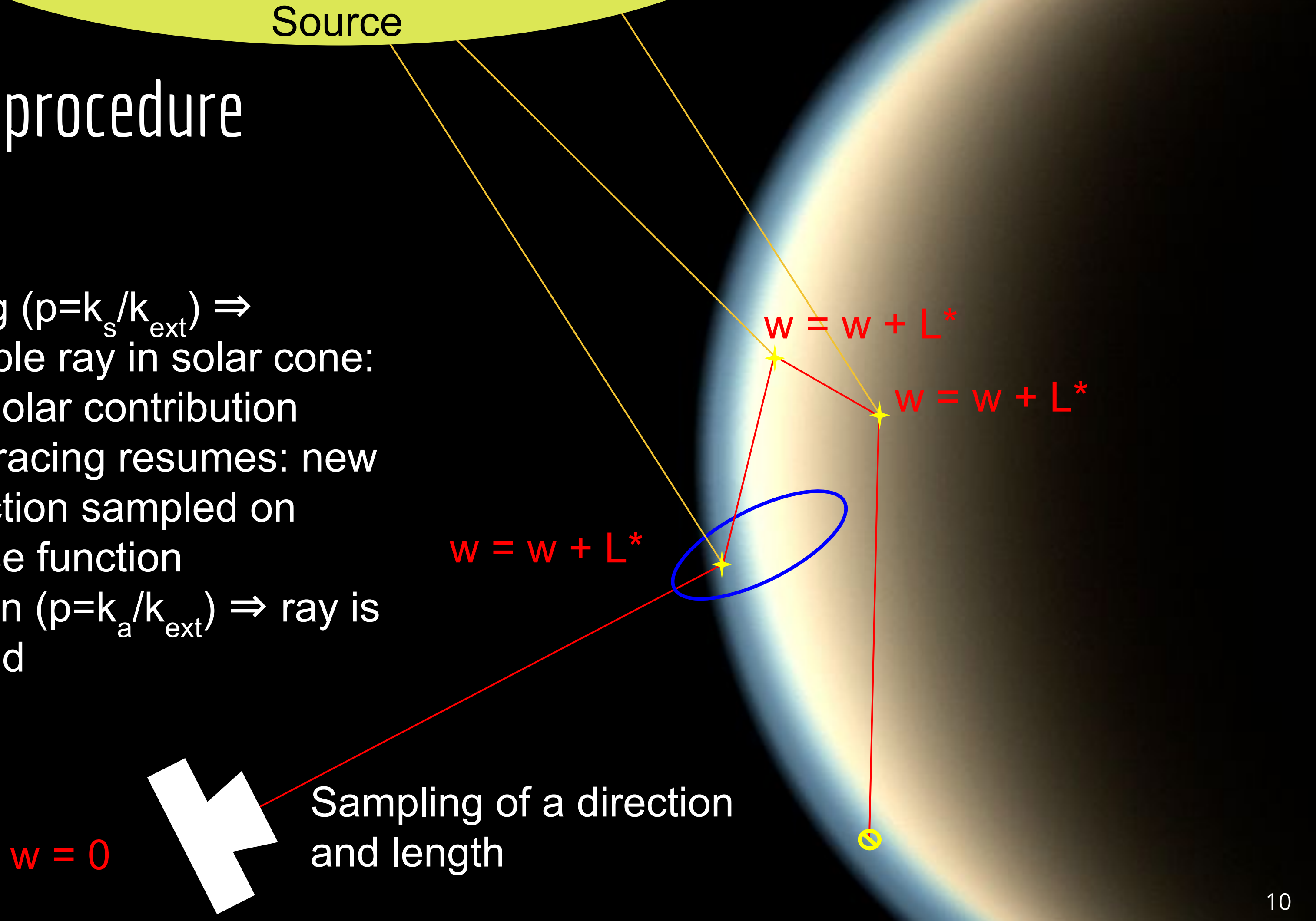
- scattering ($p=k_s/k_{ext}$) ⇒
  - sample ray in solar cone: get solar contribution
  - ray tracing resumes: new direction sampled on phase function
- absorption ($p=k_a/k_{ext}$)



Ray tracing procedure

On Event:

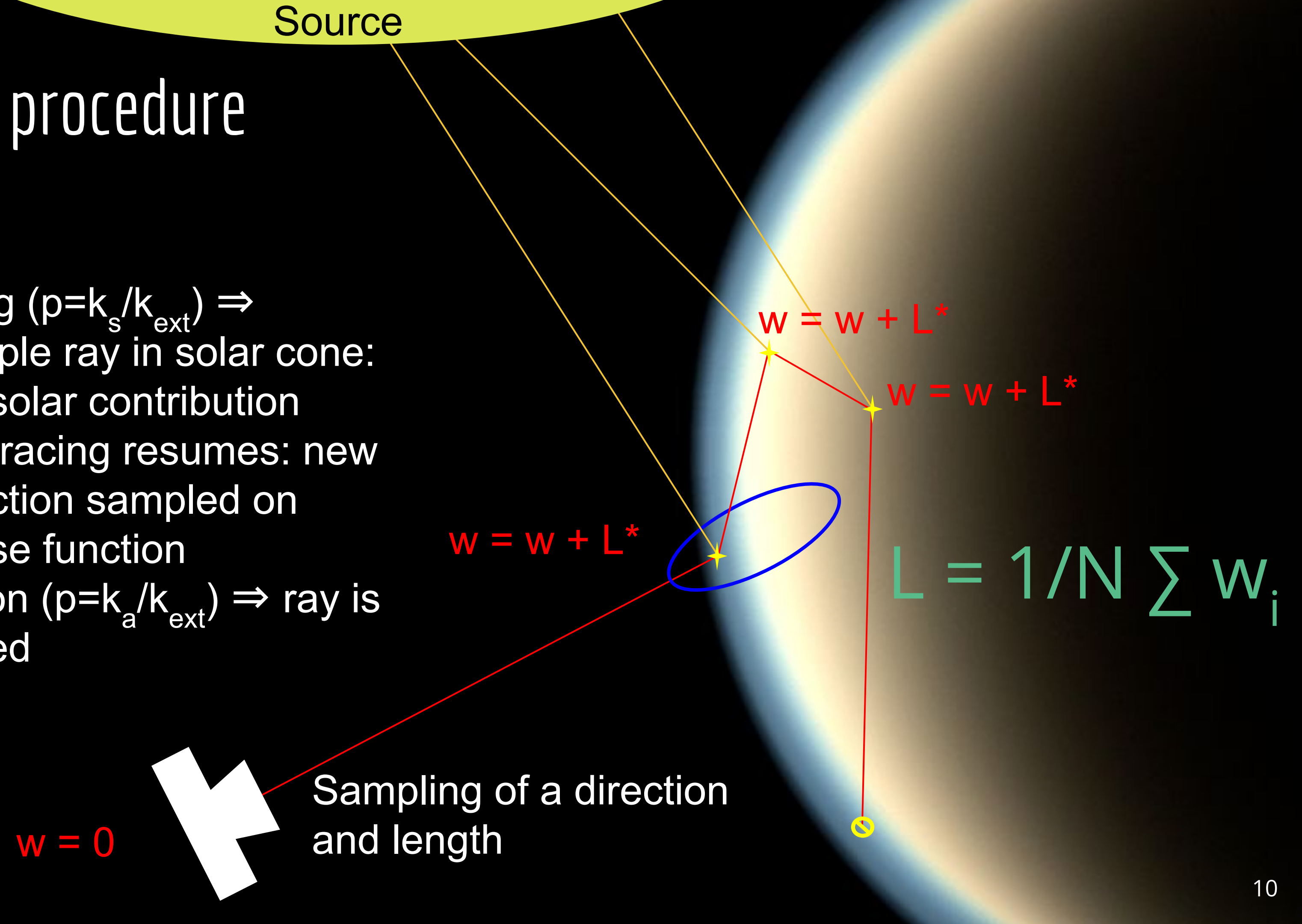
- scattering ($p=k_s/k_{ext}$) ⇒
  - sample ray in solar cone: get solar contribution
  - ray tracing resumes: new direction sampled on phase function
- absorption ($p=k_a/k_{ext}$) ⇒ ray is terminated



Ray tracing procedure

On Event:

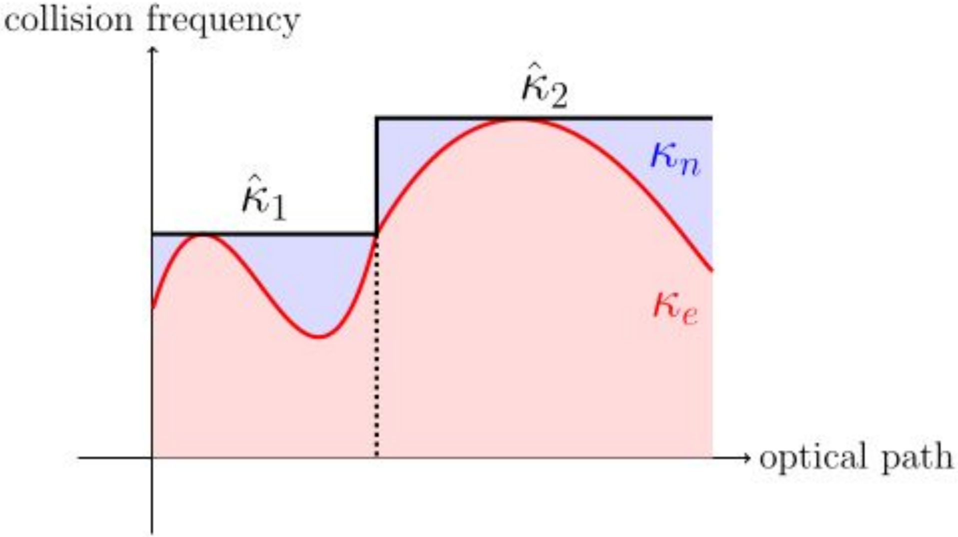
- scattering ($p=k_s/k_{ext}$) ⇒
  - sample ray in solar cone: get solar contribution
  - ray tracing resumes: new direction sampled on phase function
- absorption ($p=k_a/k_{ext}$) ⇒ ray is terminated



Nul-collision algorithm

On Event:

- scattering ($p=k_s/k_{max}$) ⇒
  - sample ray in solar cone: get solar contribution
  - ray tracing resumes: new direction sampled on phase function
- absorption ($p=k_a/k_{max}$) ⇒ ray is terminated
- nul-collision ($p=1-(k_a+k_s)/k_{max}$) ⇒ ray tracing resumes in same direction



He et al. (2026)

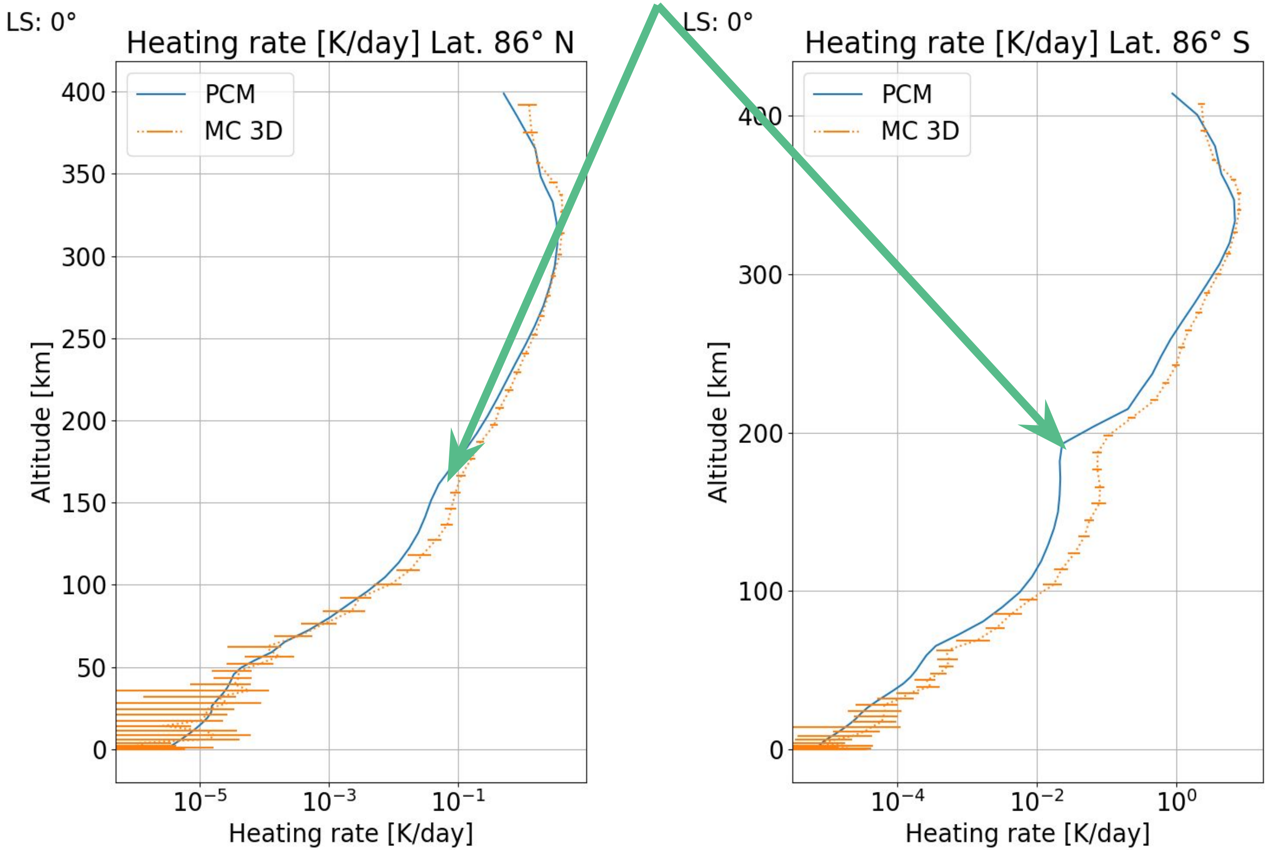
Heterogeneity effects

North / South asymmetry below 200 km

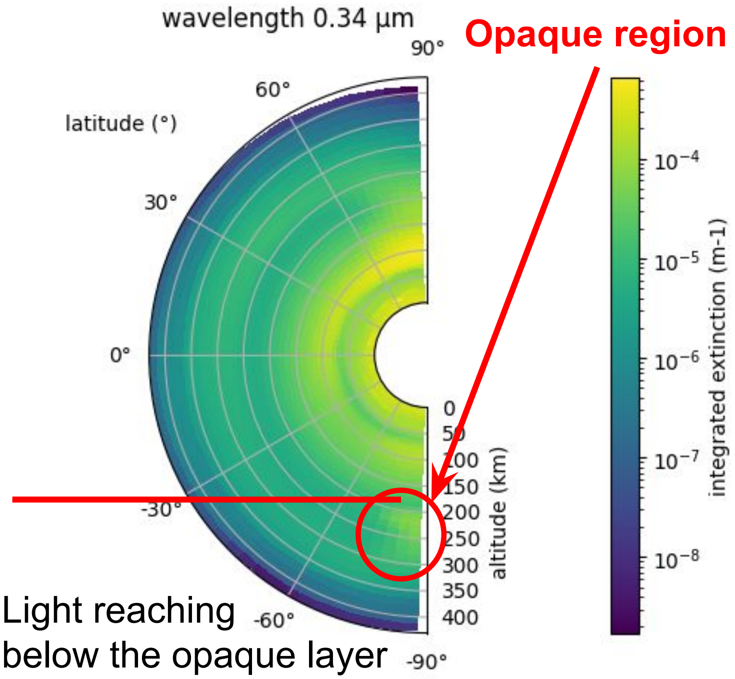
Zonal average

Northern spring equinoxe

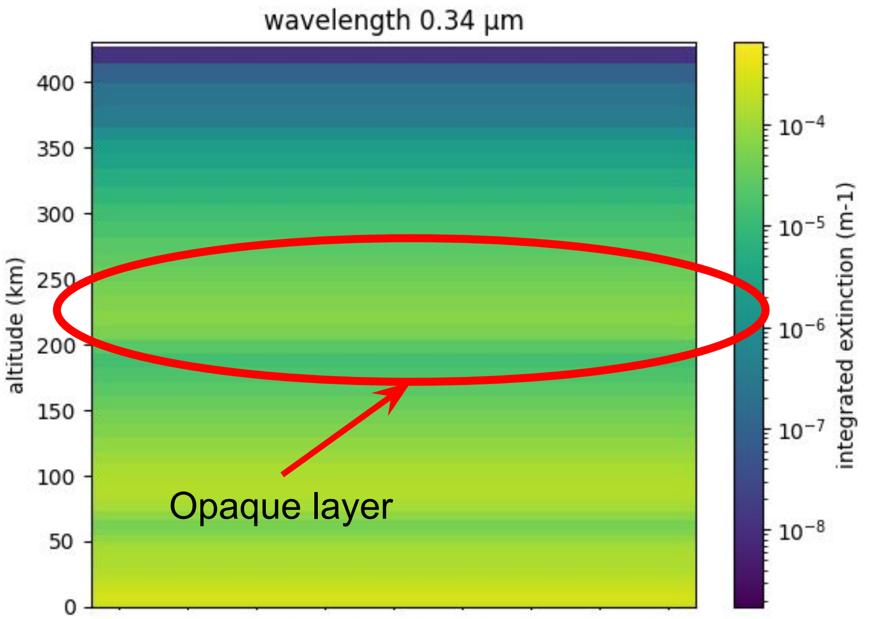
Comparing North and South poles



Heterogeneity effects

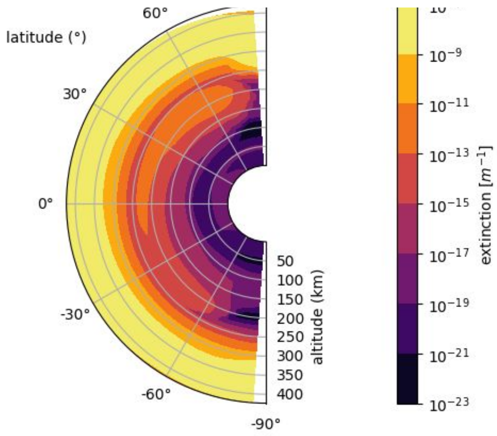


What a plane-parallel would see:



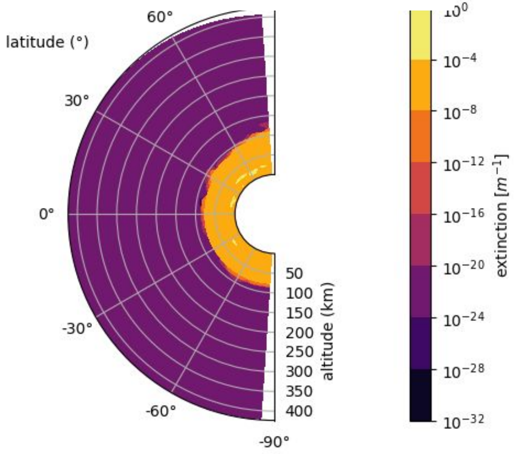
Heterogeneity effects

Small particles extinction

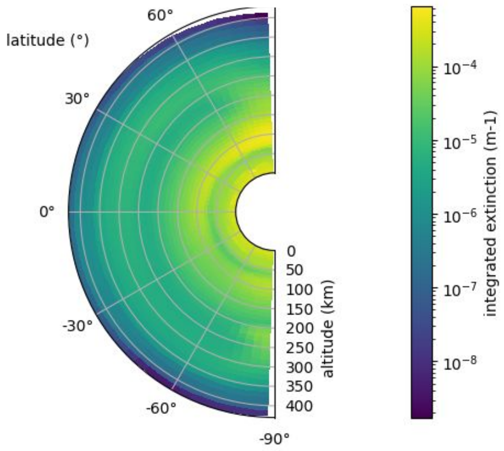


"Patch" of haze detached by circulation

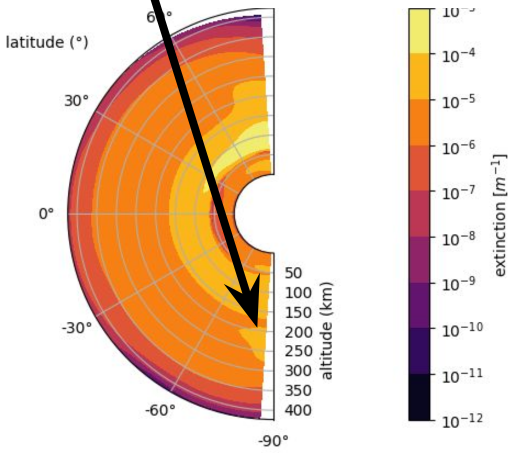
Cloud particles extinction



Total extinction



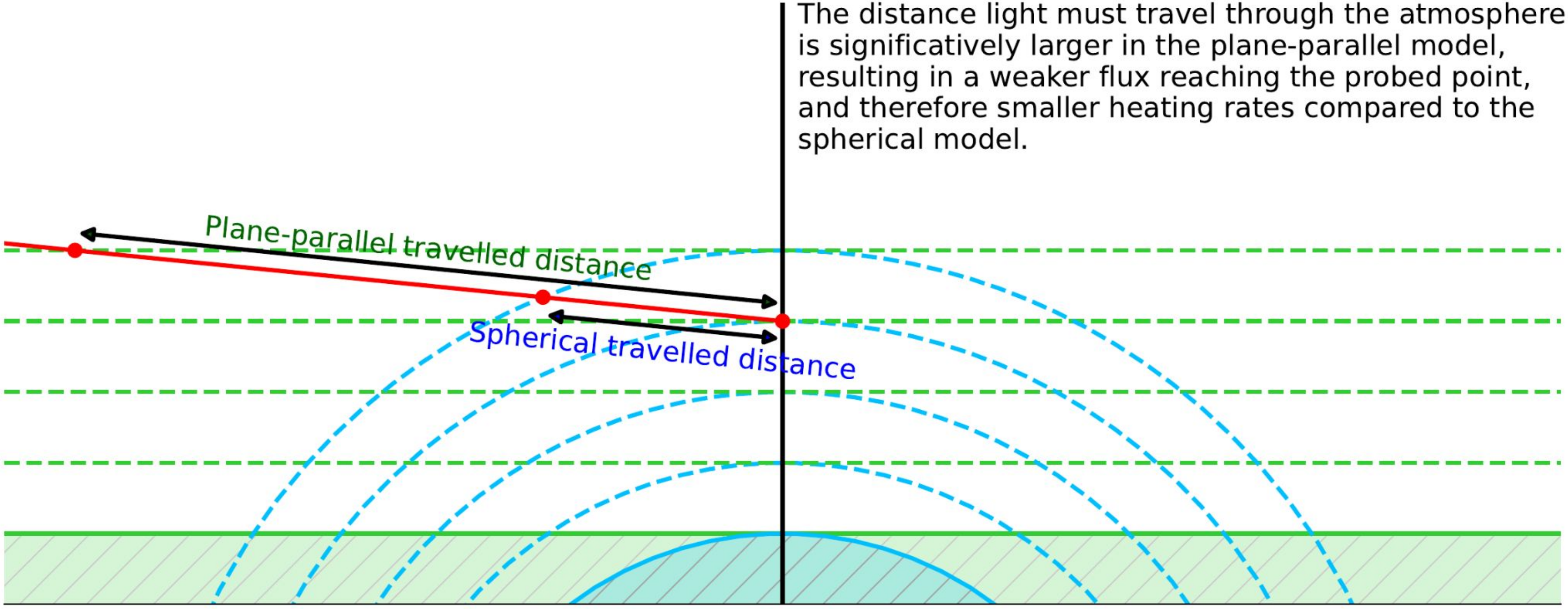
Fractal aggregates extinction



Terminator effects

Higher heating rates along the terminator

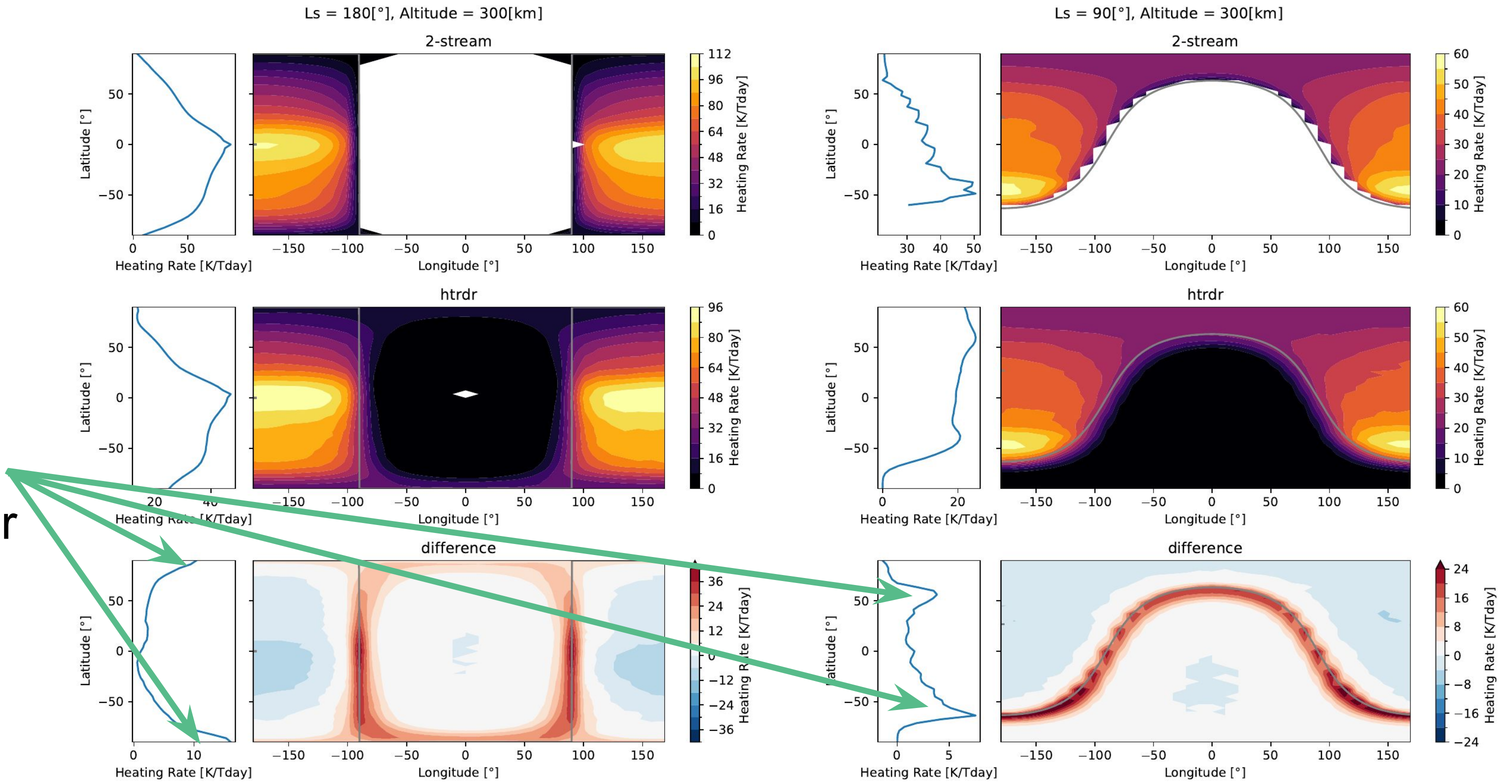
The distance light must travel through the atmosphere is significatively larger in the plane-parallel model, resulting in a weaker flux reaching the probed point, and therefore smaller heating rates compared to the spherical model.



Terminator effects

Differences along the terminator

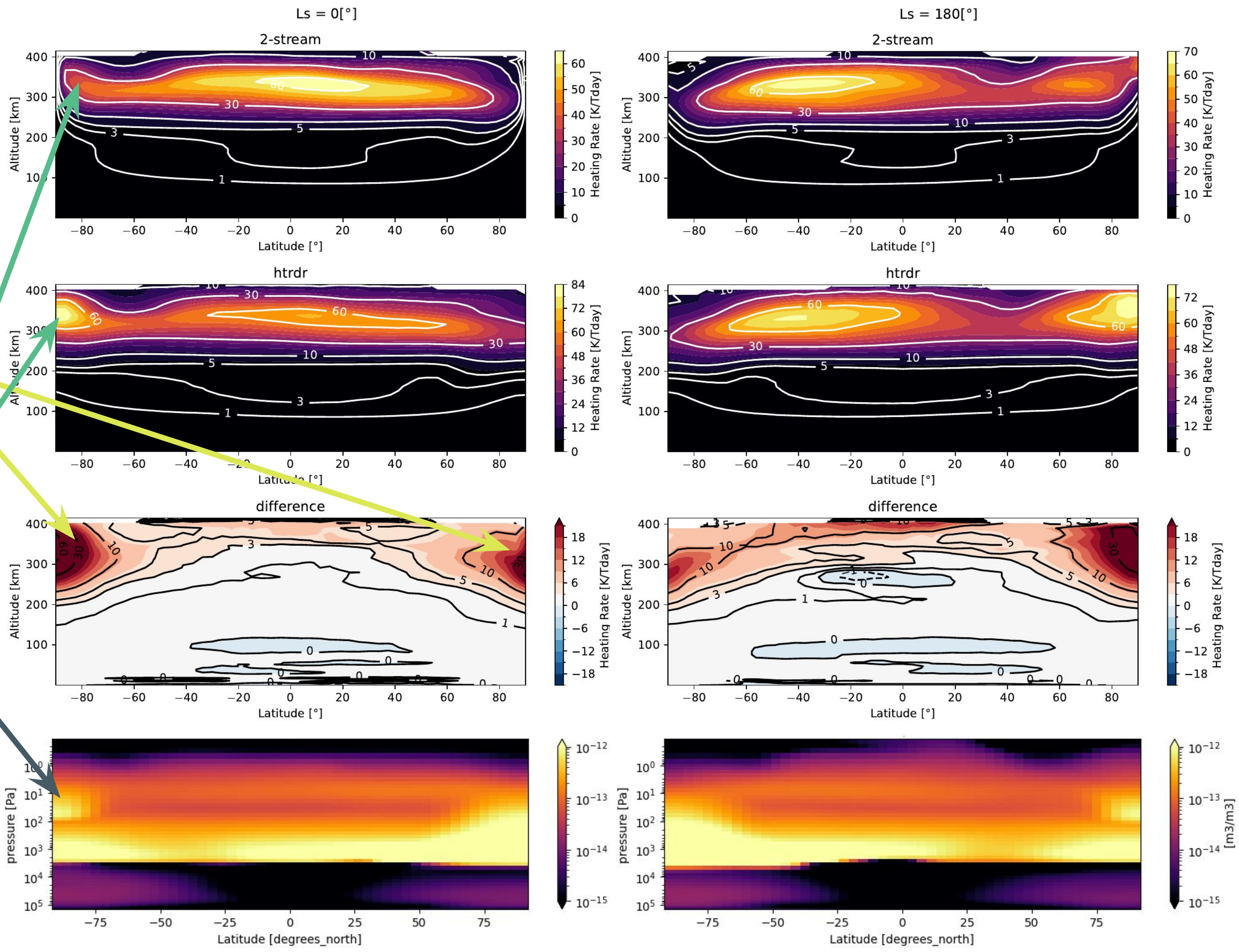
Stronger effects near limits of polar night/day



Equinoxes

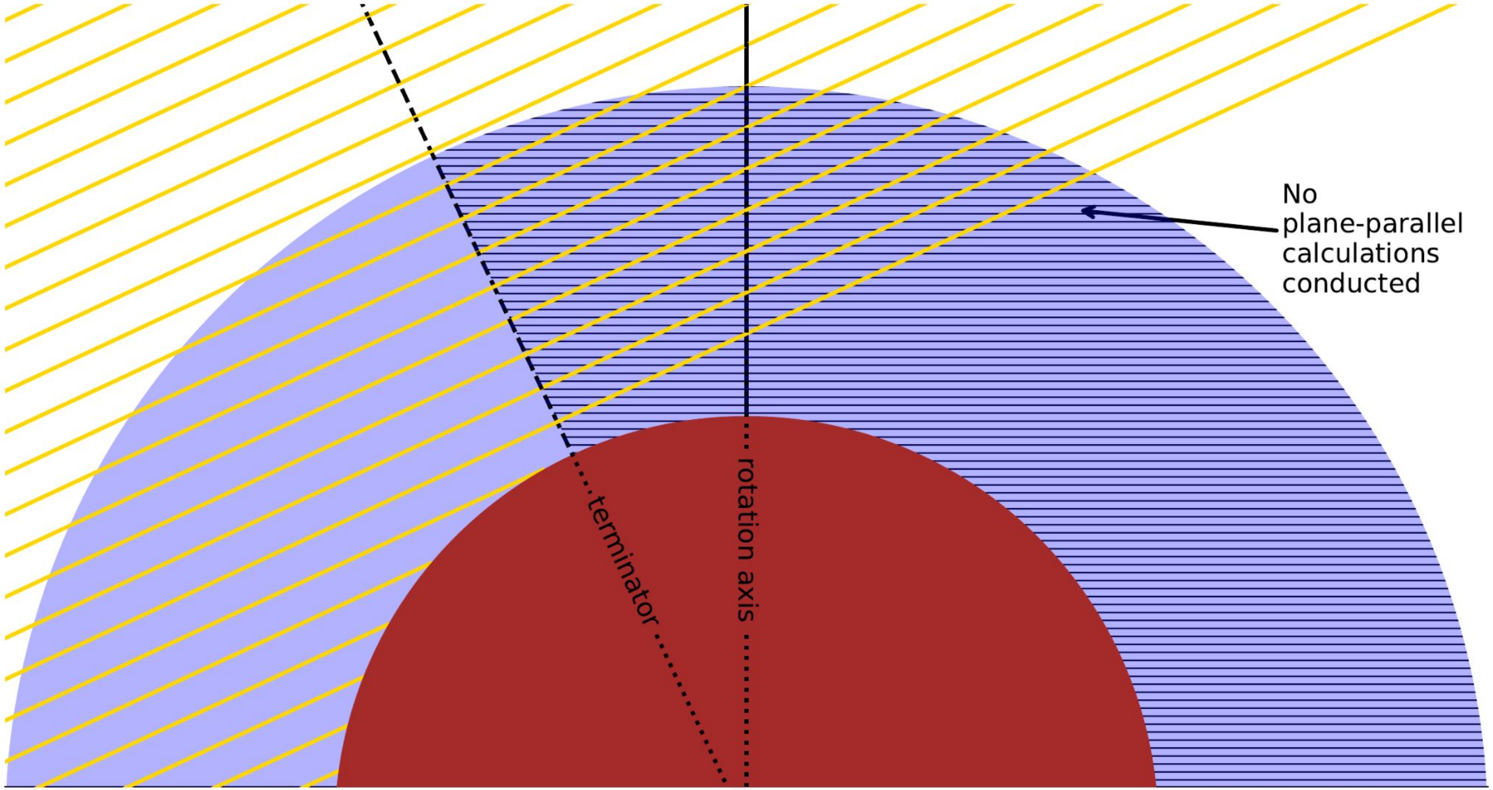
Main differences at the poles

Higher heating rates above former summer poles: detached haze layer at the limb

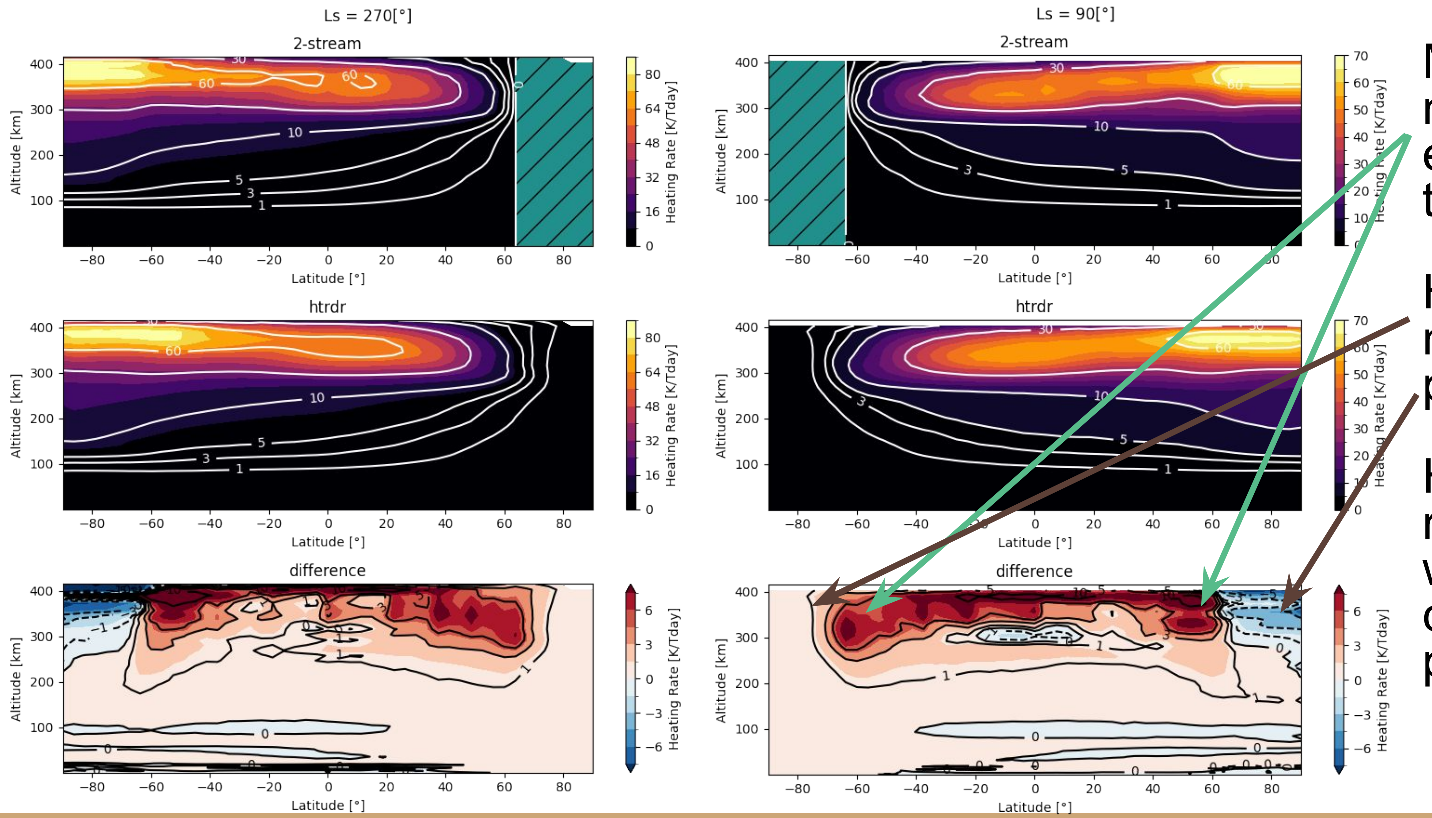


Effects on the polar regions

Higher heating rates in the polar regions



Solstices

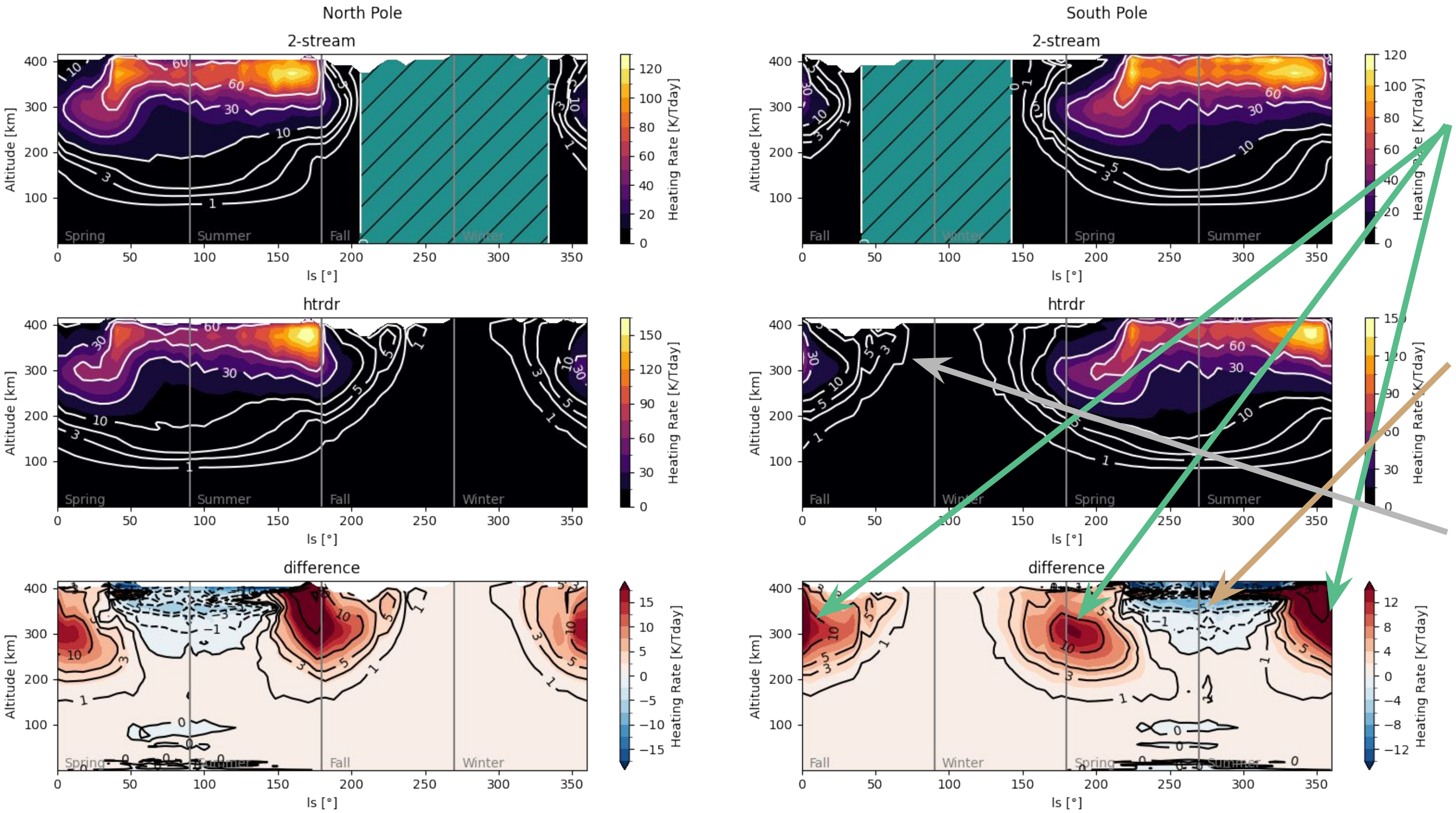


Main differences near 60° latitude: effect of terminator

Hotter polar night, cooler polar day

Higher heating rates at northern winter solstice: closer to periastron

Effects on the polar regions



Main differences at equinoxes

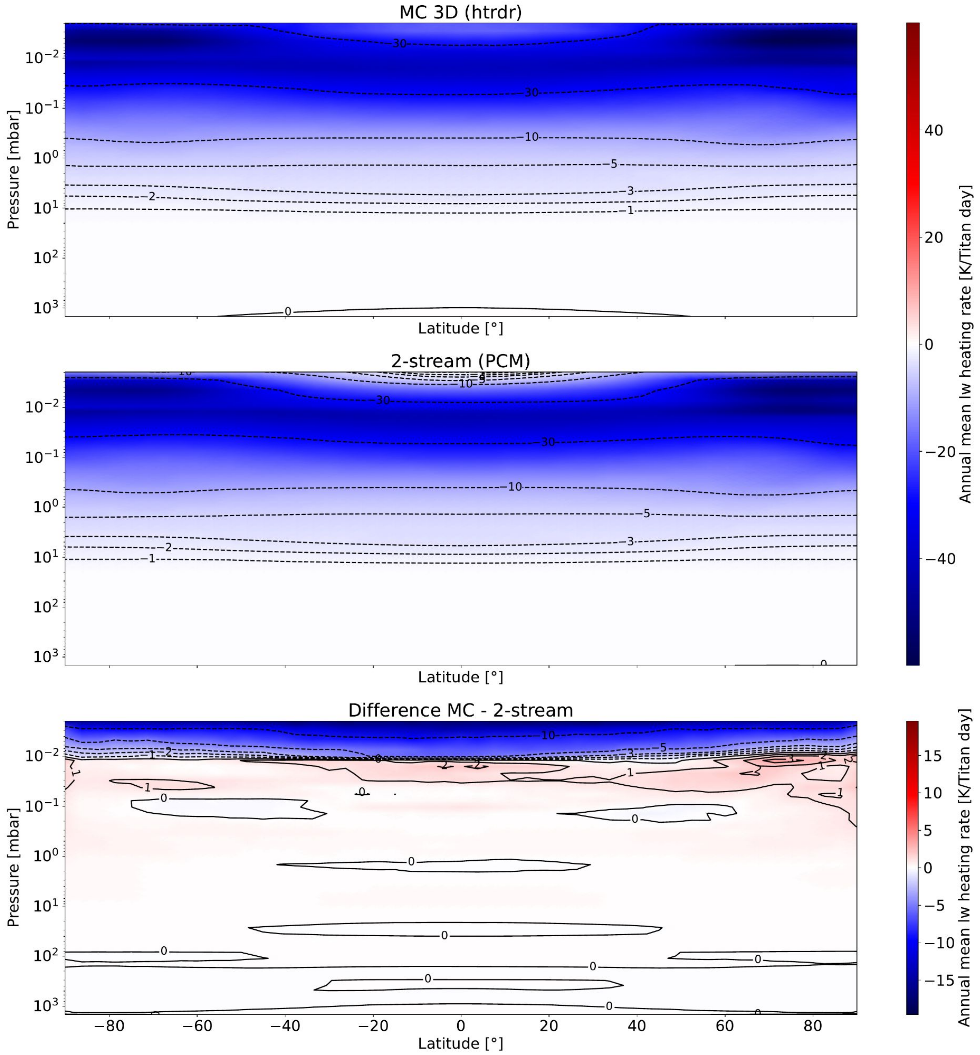
Lower heating rates during spring/summer

Non-zero heating rates in the polar region during winter

Longwave (LW)

Main differences very high up: boundary conditions of the PCM?

Small differences in main part of the atmosphere.



Coupling

1 calculation every Titan week (= 11 Titan days)

Calculation conducted on the sphere: Longitude $\Leftarrow\Rightarrow$ Local time

~50’000 samples per PCM cell

20-30 min calculation time on Roméo (+50% time on PCM)

Interpolation in Ls with previous year calculation

14 Titan years have run

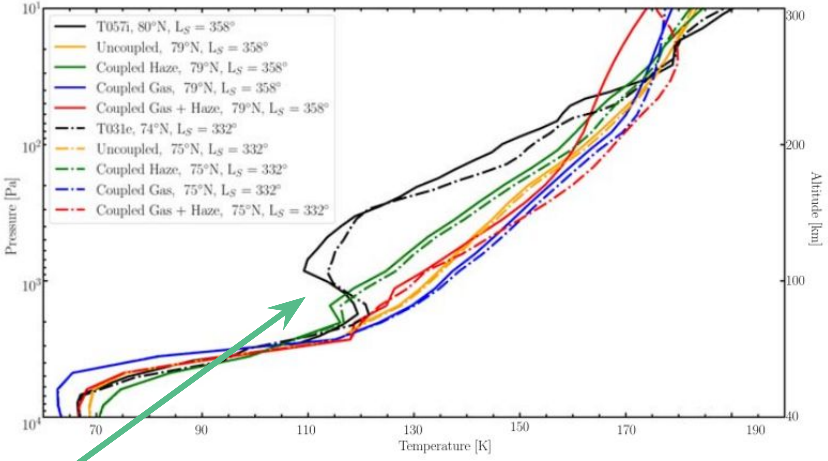
Reference case: polar shoulder

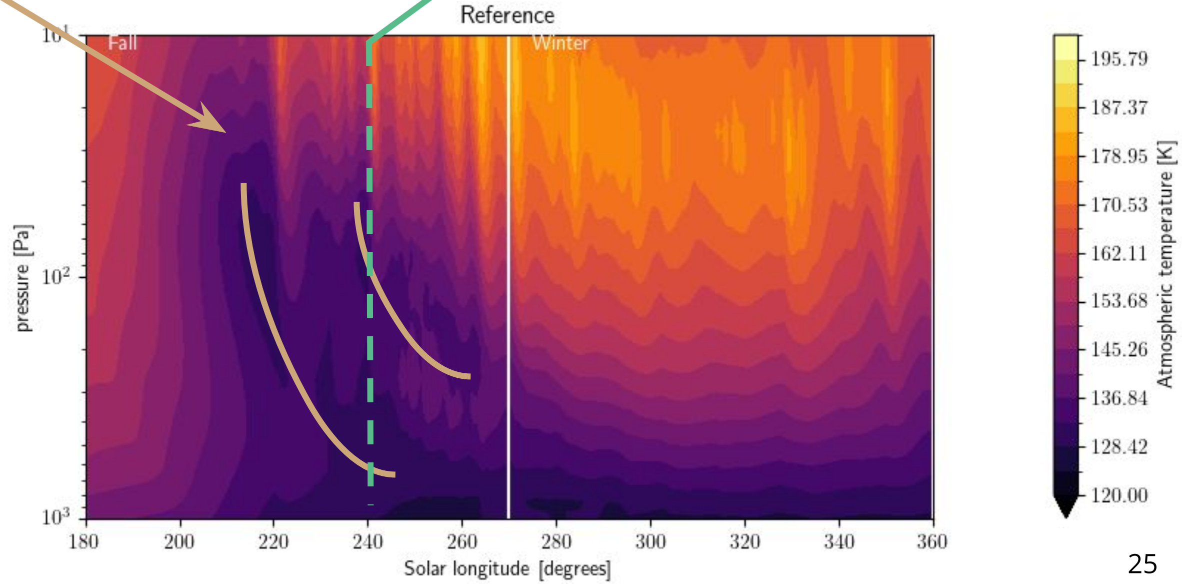
First cooling in upper atmosphere

Descent to deeper layers

Second descent of cooler air

Hotter atmosphere trapped between cold layers





Reference case: polar shoulder

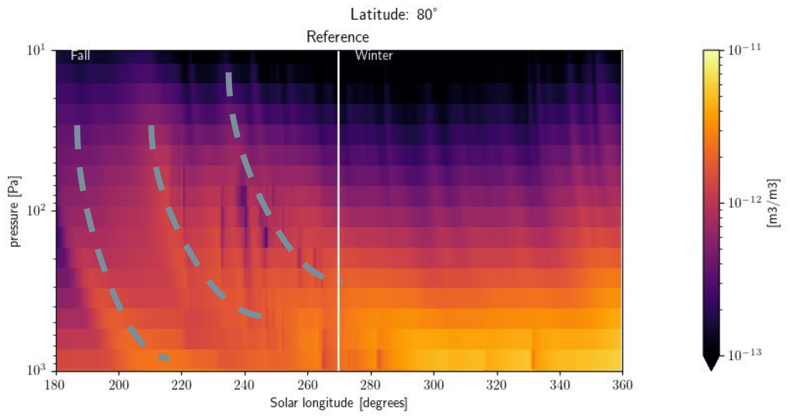
First cooling in upper atmosphere

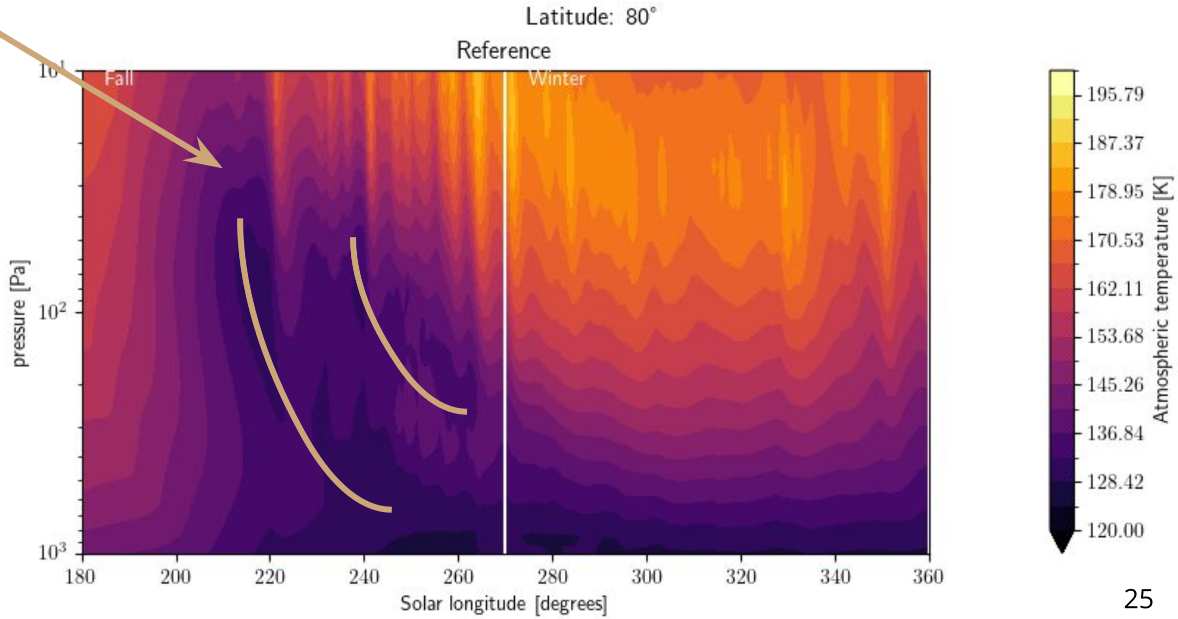
Descent to deeper layers

Second descent of cooler air

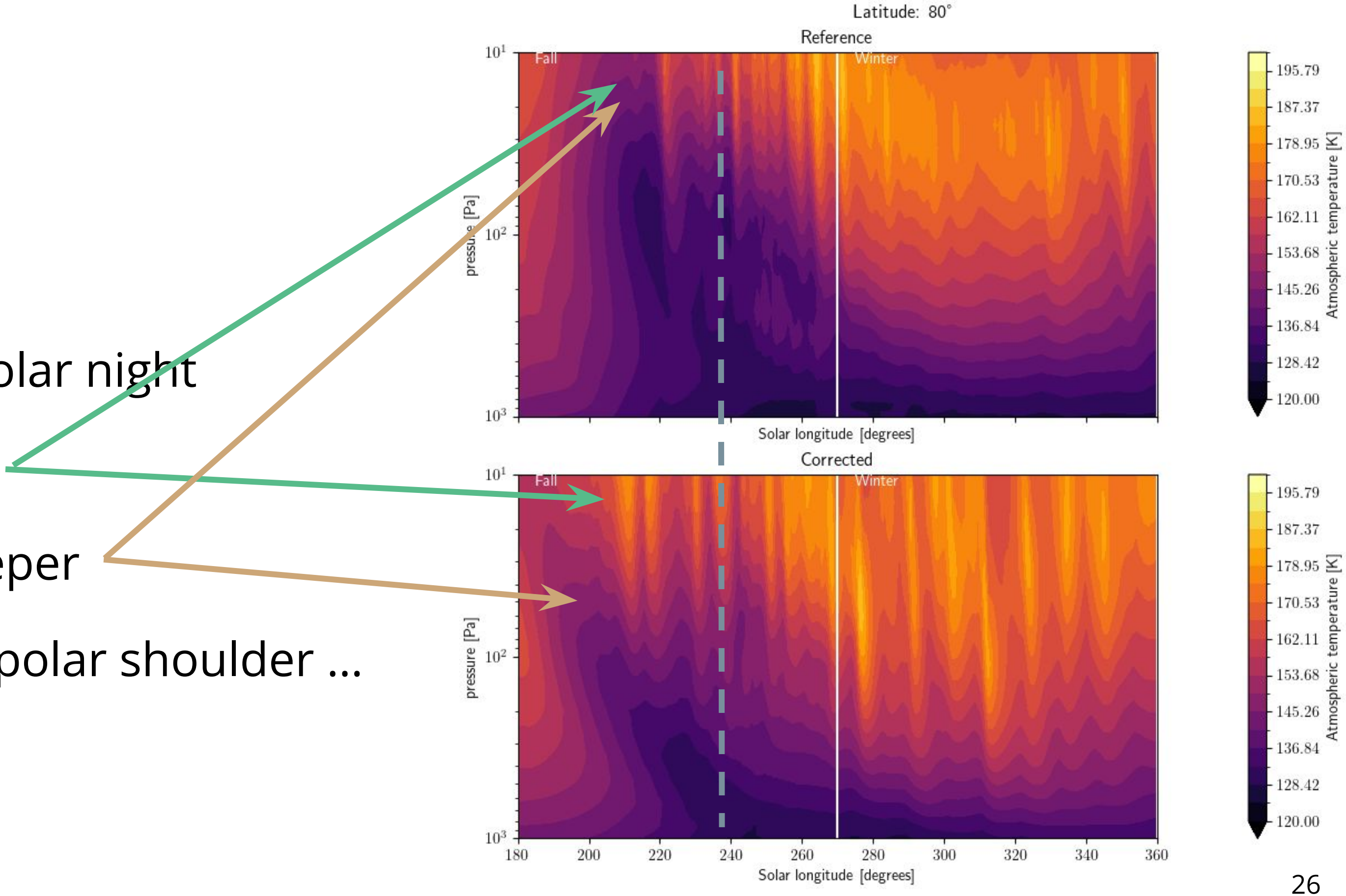
Hotter atmosphere trapped between cold layers

Due to successive descent of haze particles





Preliminary results: temperature



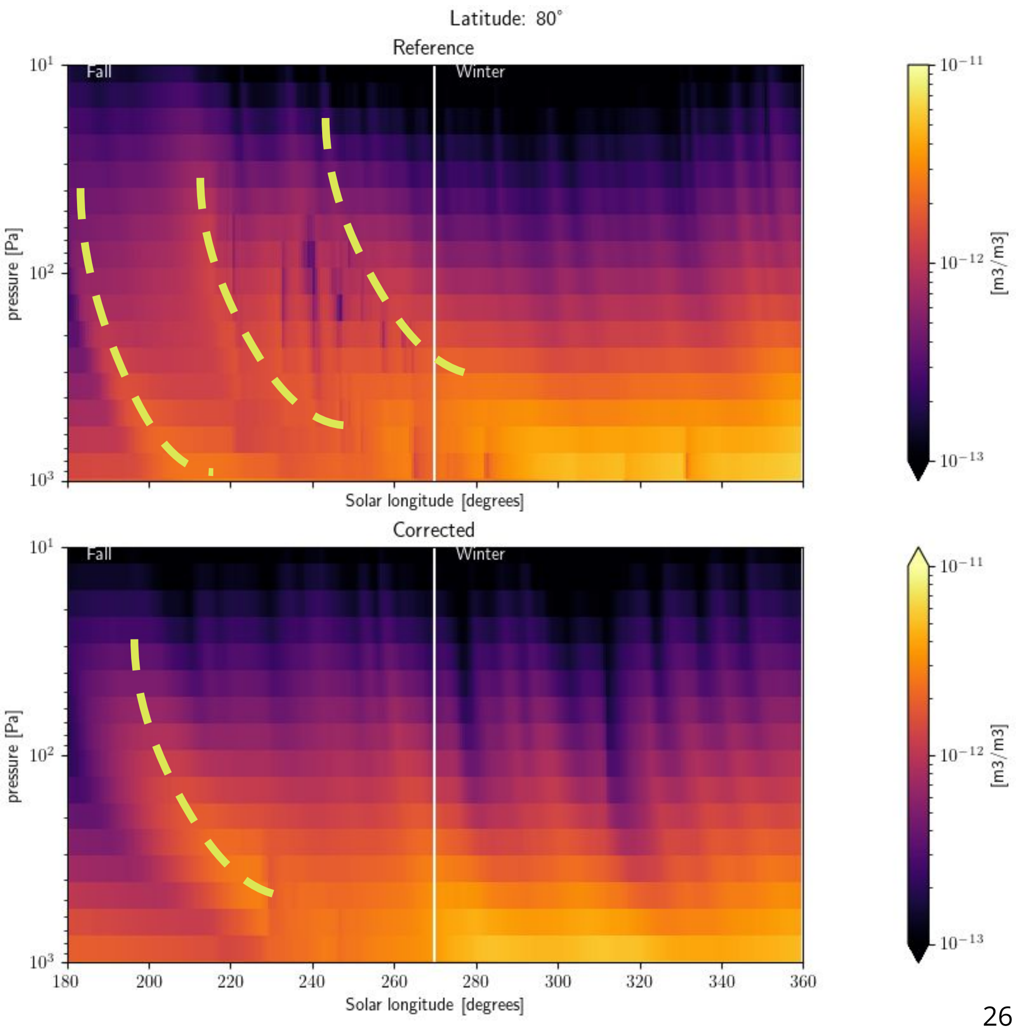
Heating within the polar night

Hotter atmosphere

Cooling happens deeper

Disapparition of the polar shoulder …

Preliminary results: haze



With correction: single descent

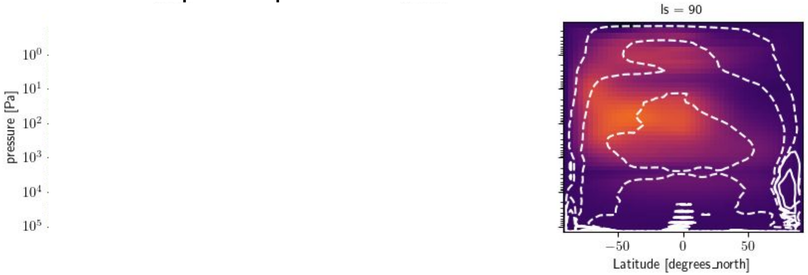
⇒ Effects on circulation ?

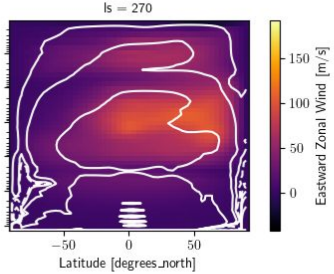
Preliminary results: circulation

Color Scale: zonal wind
White lines: meridional circulation
Dotted: anti-clockwise rotation
Solid: clockwise rotation

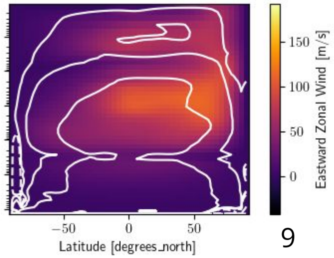
Northern spring **Northern summer** **Northern fall** **Northern winter**

Reference (plane-parallel)

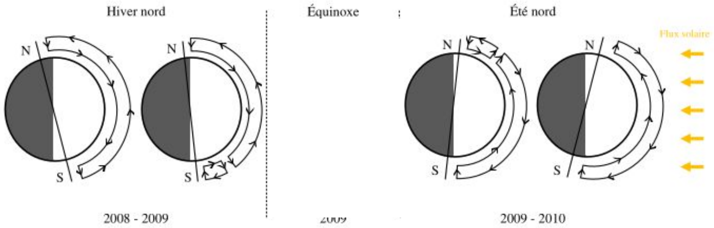




Coupled (3D radiative transfer)



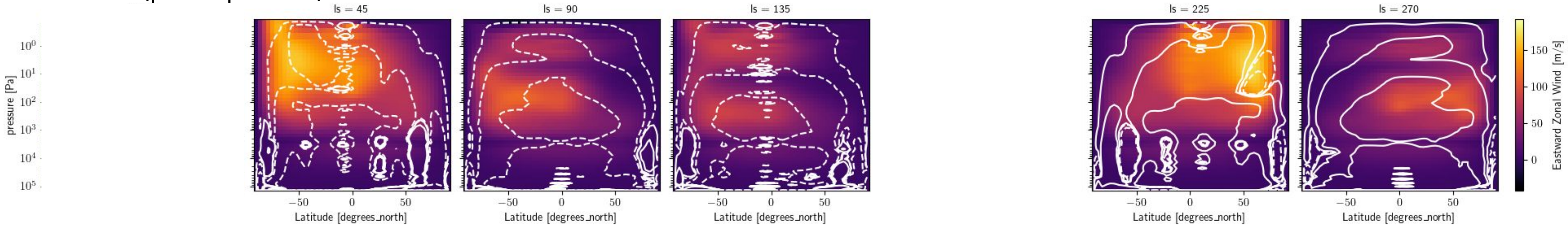
Preliminary results: circulation



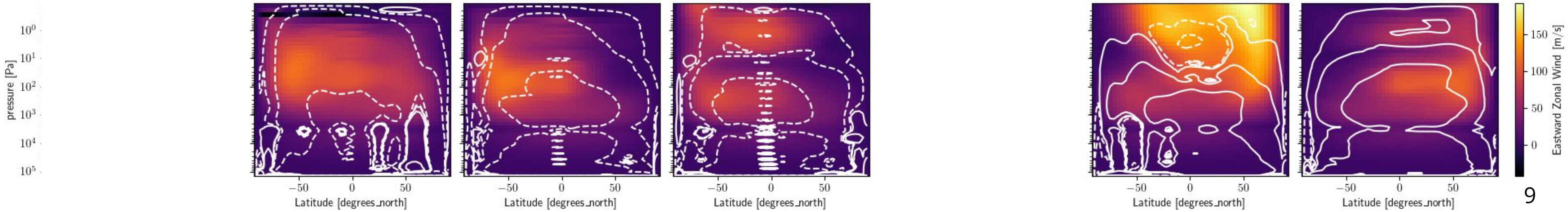
Color Scale: zonal wind
White lines: meridional circulation
Dotted: anti-clockwise rotation
Solid: clockwise rotation

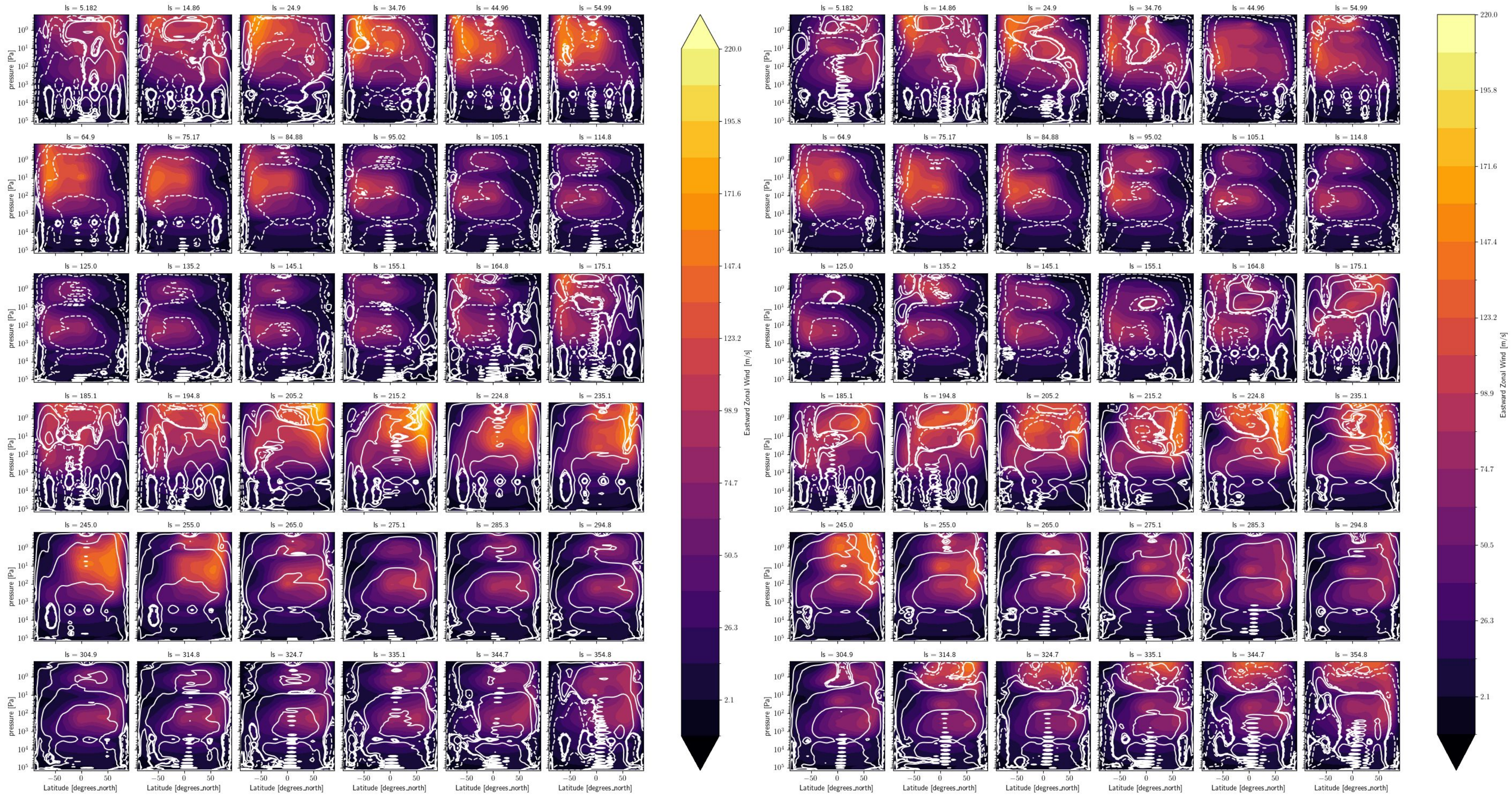
Northern spring Northern summer Northern fall Northern winter

Reference (plane-parallel)



Coupled (3D radiative transfer)




ls = 5.182
ls = 14.86
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ls = 34.76
ls = 44.96
ls = 54.99
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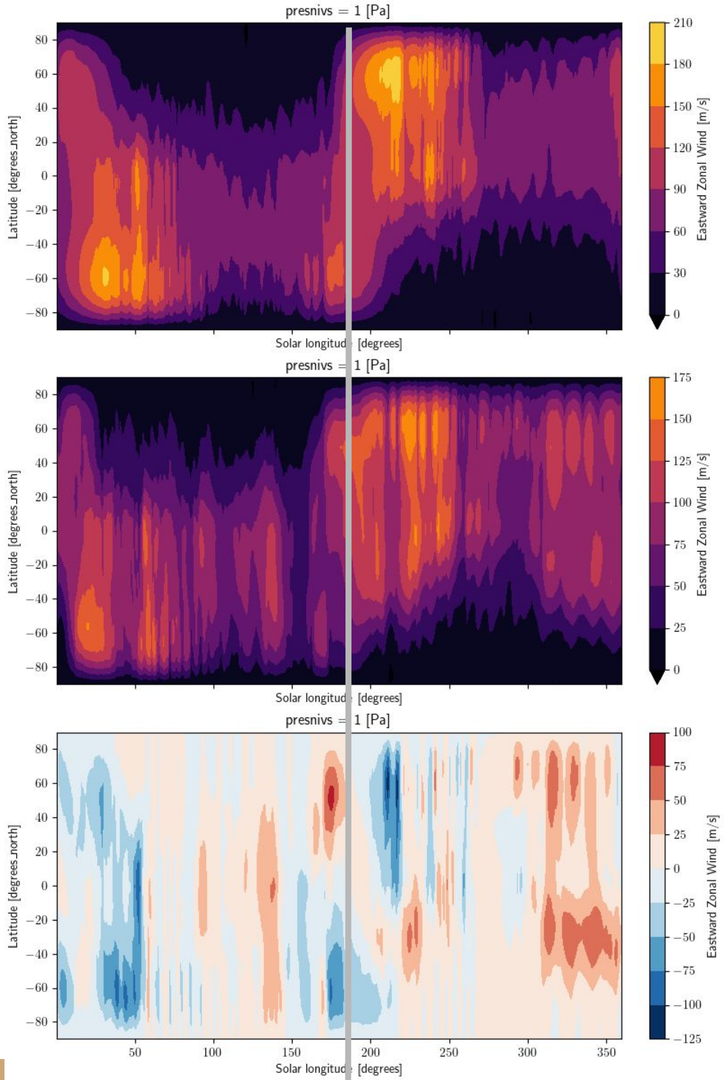
ls = 84.88
ls = 95.02
ls = 105.1
ls = 114.8
ls = 125.0
ls = 135.2
ls = 145.1
ls = 155.1
ls = 164.8
ls = 175.1
ls = 185.1
ls = 194.8
ls = 205.2
ls = 215.2
ls = 224.8
ls = 235.1
ls = 245.0
ls = 255.0
ls = 265.0
ls = 275.1
ls = 285.3
ls = 294.8
ls = 304.9
ls = 314.8
ls = 324.7
ls = 335.1
ls = 344.7
ls = 354.8
pressure [Pa]
Latitude [degrees_north]
Eastward Zonal Wind [m/s]
220.0
195.8
171.6
147.4
123.2
98.9
74.7
50.5
26.3
2.1

Preliminary results: circulation

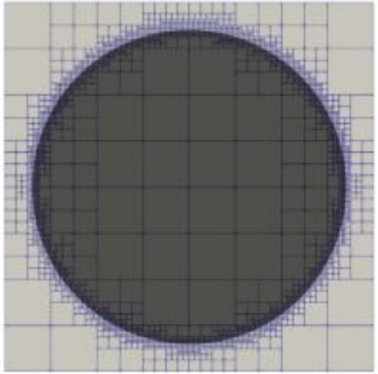
Changes in the structure of the zonal wind

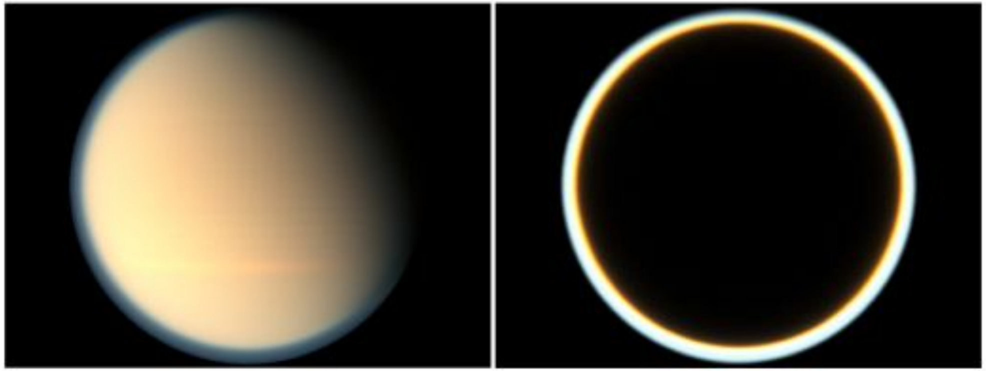
More variability in strength

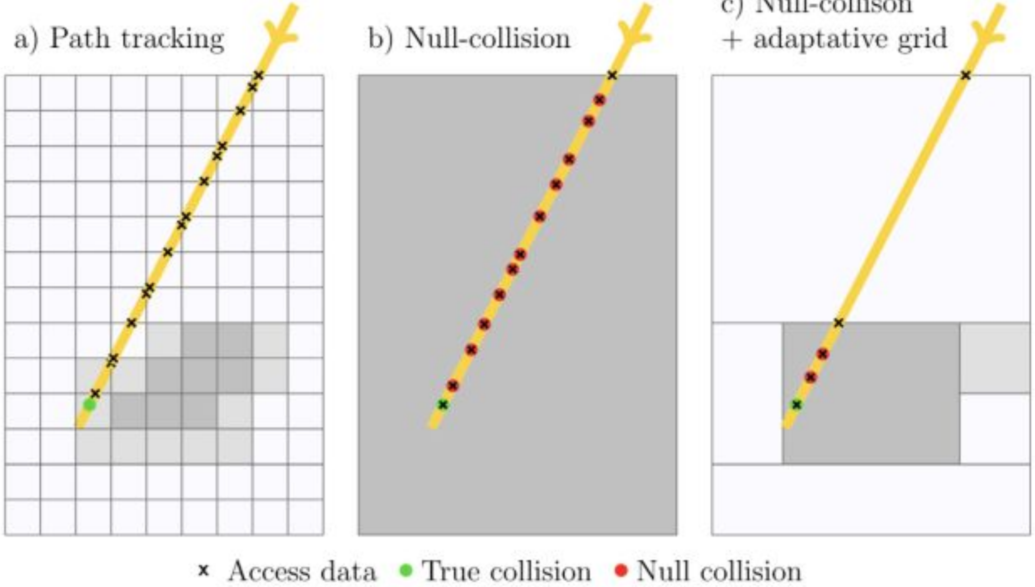
Inversion from south to north earlier



Nul-collision







He et al. (2025)

A control variates technique for the null-collision Monte Carlo algorithms

Zili He[a], Anthony Arfaux[a,b], Yaniss Nyffenegger-Péré[c], Nada Mourtaday[d]

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[b]*GSMA, UMR CNRS 6089, Université de Reims Champagne-Ardenne, Reims, France*
[c]*Instituto de Astrofísica de Andalucía (IAA-CSIC), Glorieta de la Astronomía s/n, 18008 Granada, Spain*
[d]*Laboratoire d'Optique Atmosphérique, CNRS, UMR 8518, Université de Lille, Lille, France*

Abstract

We propose a control variates technique to reduce the variance of null-collision Monte Carlo algorithms used for solving the Radiative Transfer Equation (RTE) in highly heterogeneous media. The method complements the classical spatially partitioned overestimate approach by additionally recording the minimum absorption coefficient within each voxel during preprocessing. During path tracing, the attenuation due to this minimum absorption is evaluated analytically, while the residual part is handled by path-samplings. This analytical treatment significantly improves convergence particularly in strongly absorbing media such as the planetary atmospheres in infrared absorbing band. The mathematical equivalence between the original and control-variates estimators is demonstrated, and numerical applications for Earth's and Titan's atmospheres confirm the expected variance reduction.

Keywords: Radiative Transfer, Monte Carlo, Control Variates, Null-collision

---

Traiter une partie du problème en analytique pour réduire la variance

Nouvel algo: une partie de l'absorption en collision-nulle est traité analytiquement

Zili et al. (submited)

Rappel: collision nulle

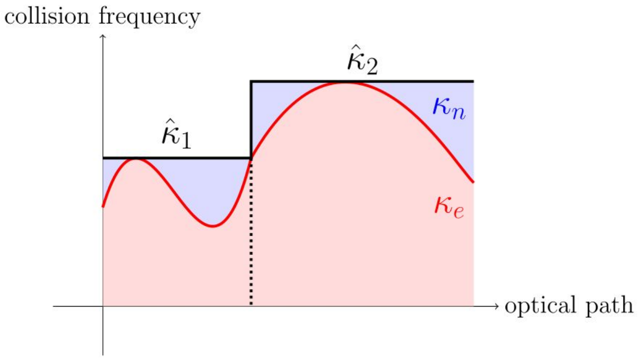
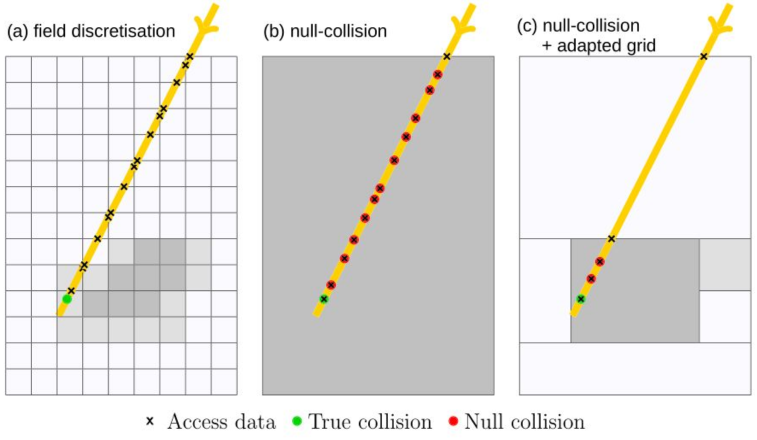


Figure 2: Example of an optical path traversing two voxels in the adapted grid. Fictitious colliders with collision frequency κ_n are added to the real, spatially varying extinction field κ_e to yield a constant overestimated extinction $\hat{\kappa}_1$ and $\hat{\kappa}_2$ within each voxels and stored during pre-processing.



Voxels homogènes: “cachent la variabilité du milieu”

Utilisation de majorant

Introduction de collision-nul

Zili et al. (submited)

Control variates

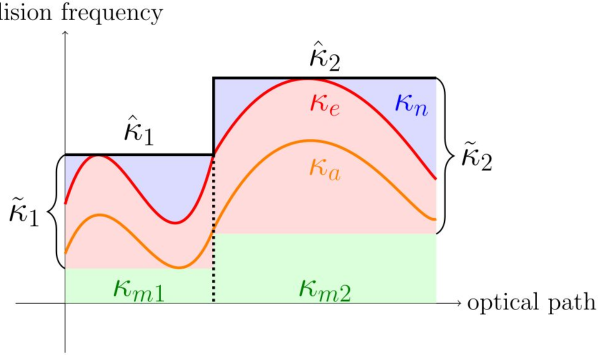


Figure 4: In addition to the maximum extinction coefficients $\hat{\kappa}_1$, $\hat{\kappa}_2$, the minimum absorption coefficients κ_{m1} and κ_{m2} are also stored during preprocessing. The reduced overestimates $\tilde{\kappa}_1 = \hat{\kappa}_1 - \kappa_{m1}$ and $\tilde{\kappa}_2 = \hat{\kappa}_2 - \kappa_{m2}$ are used to sample collision distances during path tracing.

$$w' = T_m * w + S_m$$

Here, $T_m(\vec{x}, \vec{x}')$ is the transmissivity due to κ_m between two positions, calculated analytically as:

$$T_m(\vec{x}, \vec{x}') = \prod_{i=1}^{n} \exp(-\kappa_{m_i}\sigma_i), \quad (7)$$

sum of expected values of Q_i, which are sampled within each traversed voxels (as illustrated in Fig. 6):

$$S_m(\vec{x}, \vec{x}') = \sum_{i=1}^{n} \mathbb{E}[Q_i], \quad (9)$$

with each contribution defined as:

$$\mathbb{E}[Q_i] = \prod_{j=1}^{i-1} \exp(-\kappa_{m_j}\sigma_j) \int_0^{\sigma_i} p_{\Sigma'}(\sigma')d\sigma' \cdot (1 - \exp(-\kappa_{m_i}\sigma_i)) \cdot B(\vec{x} - \vec{u}\sigma'), \quad (10)$$

On introduit un minorant de l'absorption

Cette partie (en verte) est traitée de façon analytique

Au cours du tracé, on conserve:

- La transmission le long du chemin lié au minorant
- L'émission atmosphérique le long du chemin lié au minorant

Une fois le rayon terminé, le poids est atténué par la transmission et augmenté de l'émission, liés au minorant

Zili et al. (submited)

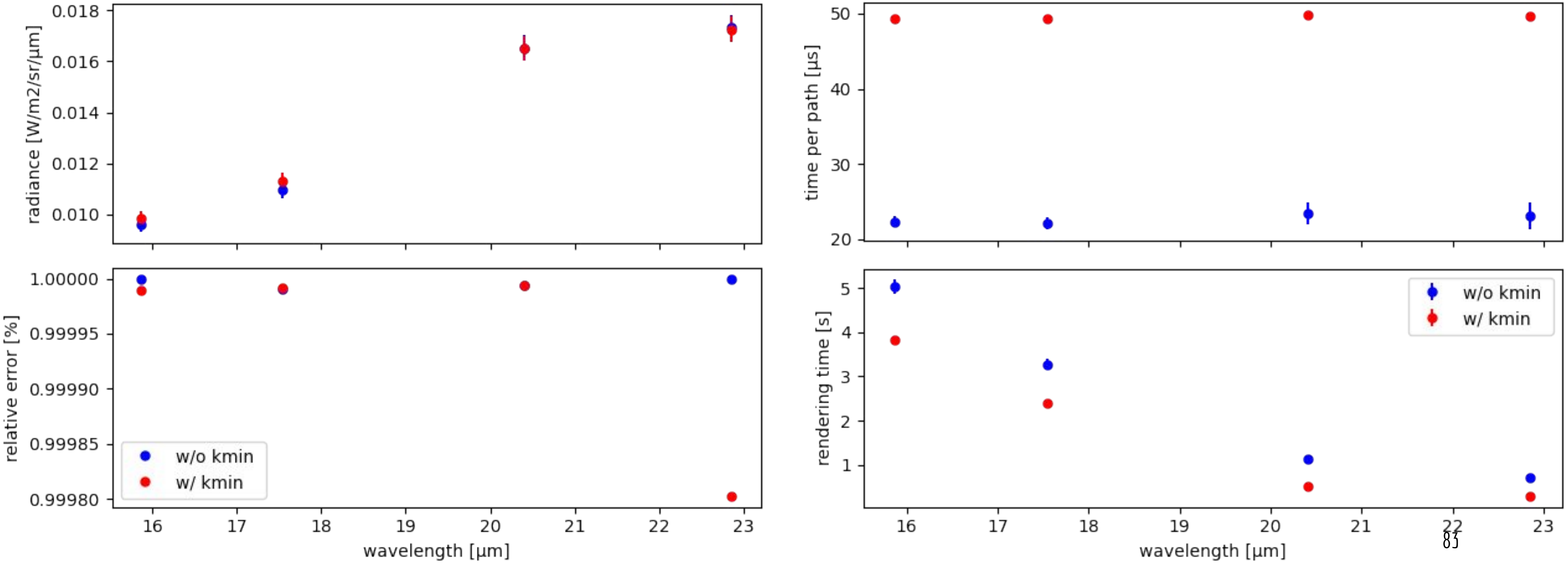
Résultats

Table B.1: Results of 1D-atmospheric slab configuration in $[W/m^2 \cdot sr \cdot \mu m]$. The number of realisation is 100000.

	Earth 650cm^{-1}	Titan 650cm^{-1}
Solution	1.94129	7.441×10^{-3}
$\kappa_m = 0$	$1.94148 \pm 6.06\times10^{-4}$	$7.564\times10^{-3} \pm 9.17\times10^{-5}$
$\kappa_m = 0.25\kappa_a$	$1.94088 \pm 4.96\times10^{-4}$	$7.418\times10^{-3} \pm 7.07\times10^{-5}$
$\kappa_m = 0.5\kappa_a$	$1.94116 \pm 3.88\times10^{-4}$	$7.533\times10^{-3} \pm 5.95\times10^{-5}$
$\kappa_m = 0.75\kappa_a$	$1.94111 \pm 2.71\times10^{-4}$	$7.453\times10^{-3} \pm 3.61\times10^{-5}$
$\kappa_m = \kappa_a$	1.94129 ± 0	$7.441\times10^{-3} \pm 0$

Table B.2: Results of the full-complexity configuration in $[W/m^2 \cdot sr \cdot \mu m]$. The number of realisation is 100000

	Titan 650cm^{-1}	Titan 579cm^{-1}
reference	$9.87\times10^{-3} \pm 2.96\times10^{-4}$	$11.04\times10^{-3} \pm 2.67\times10^{-4}$
our approach	$9.66\times10^{-3} \pm 1.59\times10^{-4}$	$11.38\times10^{-3} \pm 1.61\times10^{-4}$
	Titan 490cm^{-1}	Titan 437cm^{-1}
reference	$16.54\times10^{-3} \pm 2.24\times10^{-4}$	$17.43\times10^{-3} \pm 1.96\times10^{-4}$
our approach	$16.71\times10^{-3} \pm 1.32\times10^{-4}$	$17.52\times10^{-3} \pm 1.13\times10^{-4}$



Limitations

Calcul intermédiaire coûteux

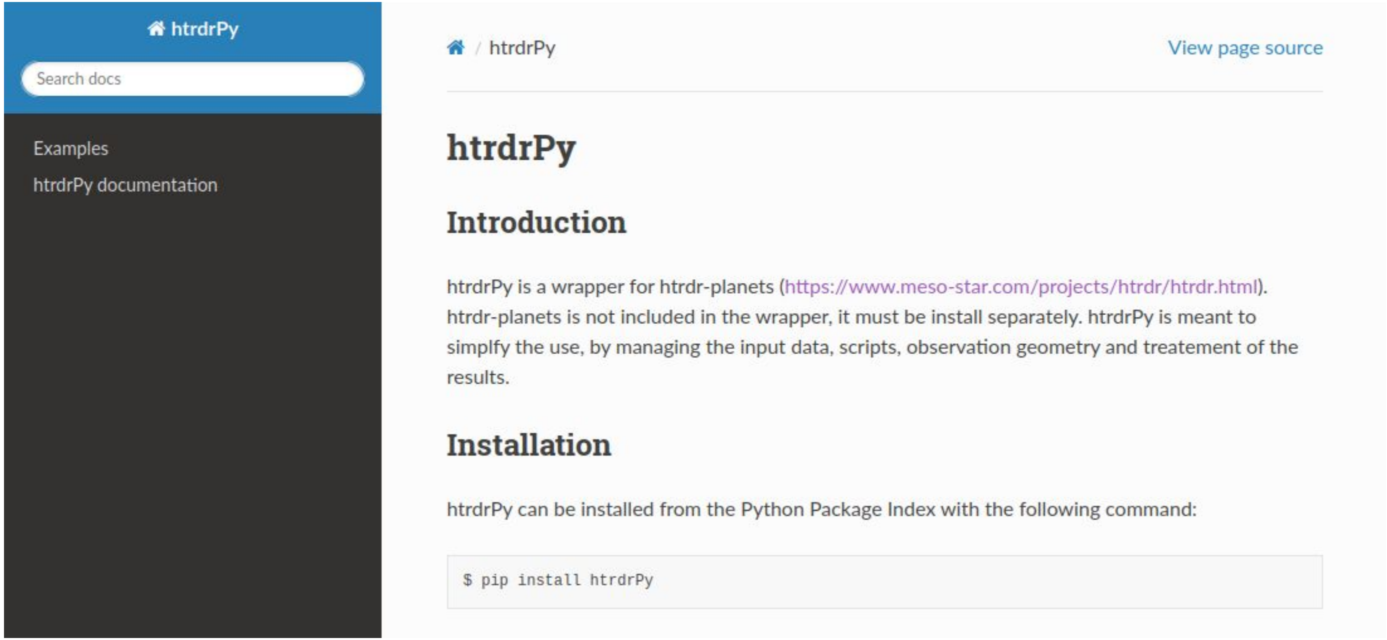
==> nécessite un cas optimal:

- Forte absorption, peu de diffusion
- Faible variabilité au sein du voxel

==> problème avec les grilles actuelles de htrdr-planets

Amélioration avec les futures grilles ?

htrdrPy



htrdrPy

Search docs

Examples

htrdrPy documentation

htrdrPy

View page source

htrdrPy

Introduction

htrdrPy is a wrapper for htrdr-planets (https://www.meso-star.com/projects/htrdr/htrdr.html). htrdr-planets is not included in the wrapper, it must be install separately. htrdrPy is meant to simplfy the use, by managing the input data, scripts, observation geometry and treatement of the results.

Installation

htrdrPy can be installed from the Python Package Index with the following command:

```
$ pip install htrdrPy
```

Documentation

GitLab

PyPi