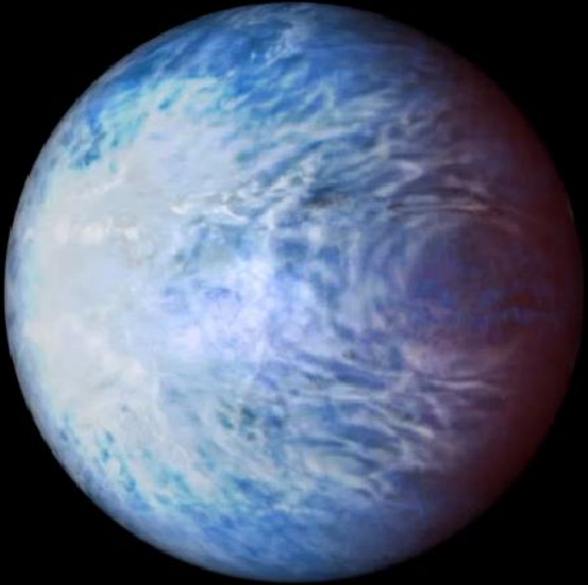
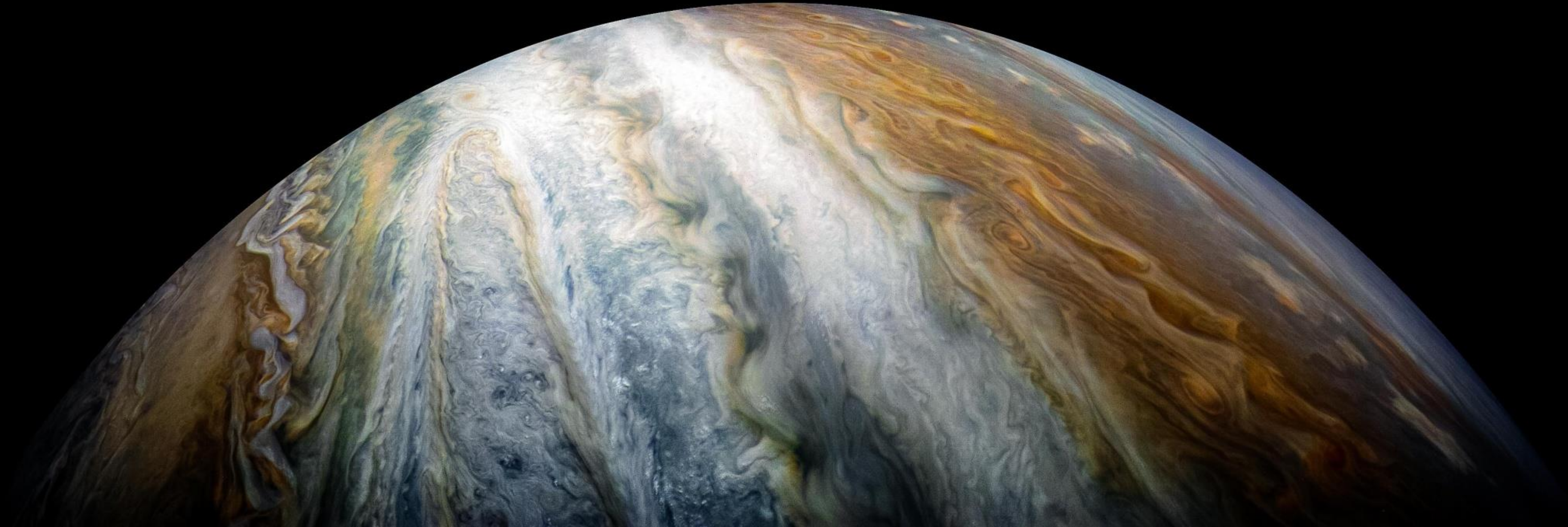
Radiative transfer for extra-solar planets: bringing it down to Earth

James Manners 23/5/18

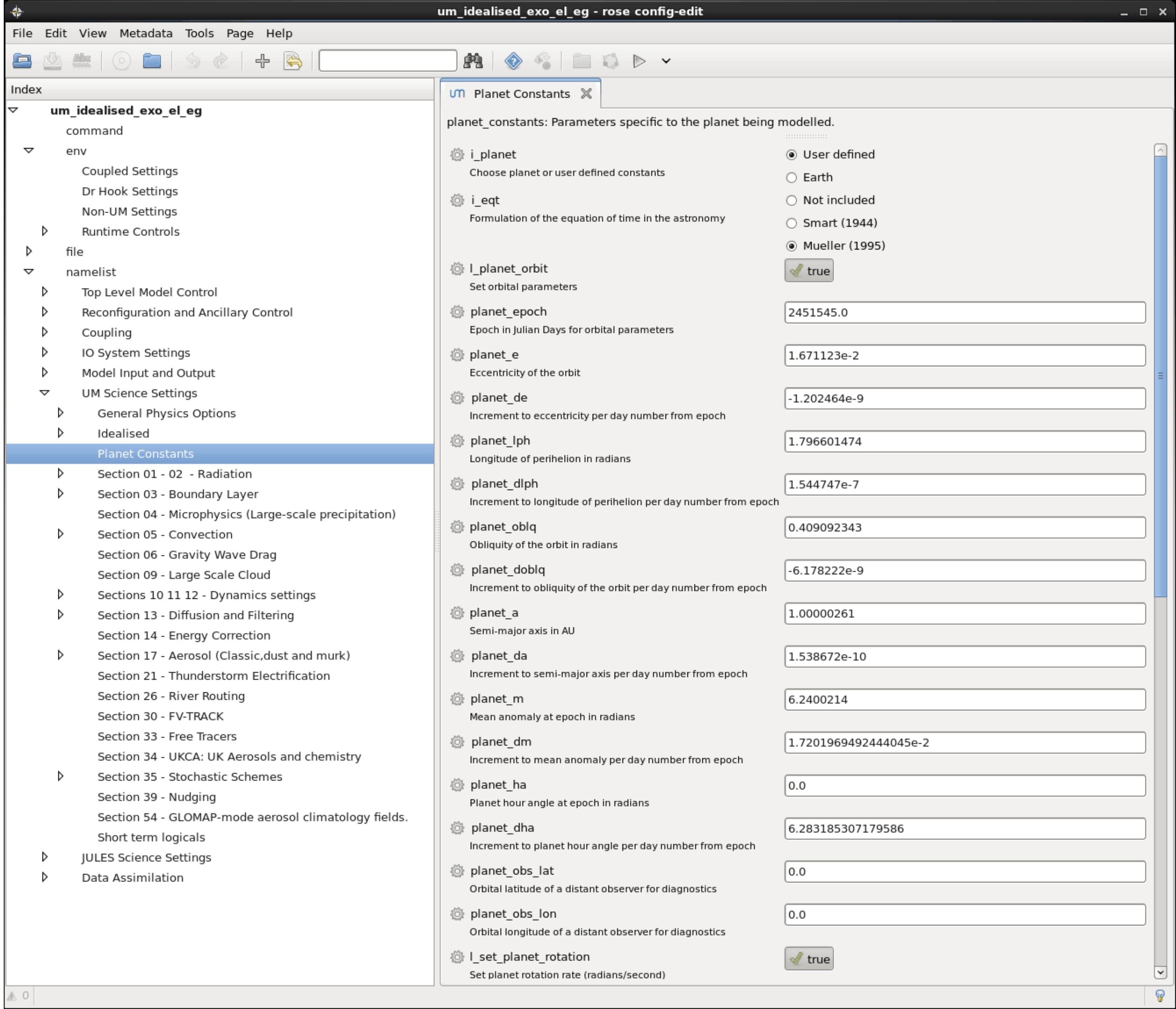


- GCM adaptations for a general planet
- Flexible radiative transfer configuration
- Techniques to generate correlated-k coefficients
- Simulated astronomical observations for exoplanets
- Treatment of spherical geometry for direct solar radiation
- Future extensions to the scheme

Simulating a general planet



Planet parameters



planet_constants: Parameters specific to the planet being modelled.

i_planet — Choose planet or user defined constants: ● User defined ○ Earth

i_eqt — Formulation of the equation of time in the astronomy: ○ Not included ○ Smart (1944) ● Mueller (1995)

l_planet_orbit — Set orbital parameters: ✓ true

planet_epoch — Epoch in Julian Days for orbital parameters: 2451545.0

planet_e — Eccentricity of the orbit: 1.671123e-2

planet_de — Increment to eccentricity per day number from epoch: -1.202464e-9

planet_lph — Longitude of perihelion in radians: 1.796601474

planet_dlph — Increment to longitude of perihelion per day number from epoch: 1.544747e-7

planet_oblq — Obliquity of the orbit in radians: 0.409092343

planet_doblq — Increment to obliquity of the orbit per day number from epoch: -6.178222e-9

planet_a — Semi-major axis in AU: 1.00000261

planet_da — Increment to semi-major axis per day number from epoch: 1.538672e-10

planet_m — Mean anomaly at epoch in radians: 6.2400214

planet_dm — Increment to mean anomaly per day number from epoch: 1.7201969492444045e-2

planet_ha — Planet hour angle at epoch in radians: 0.0

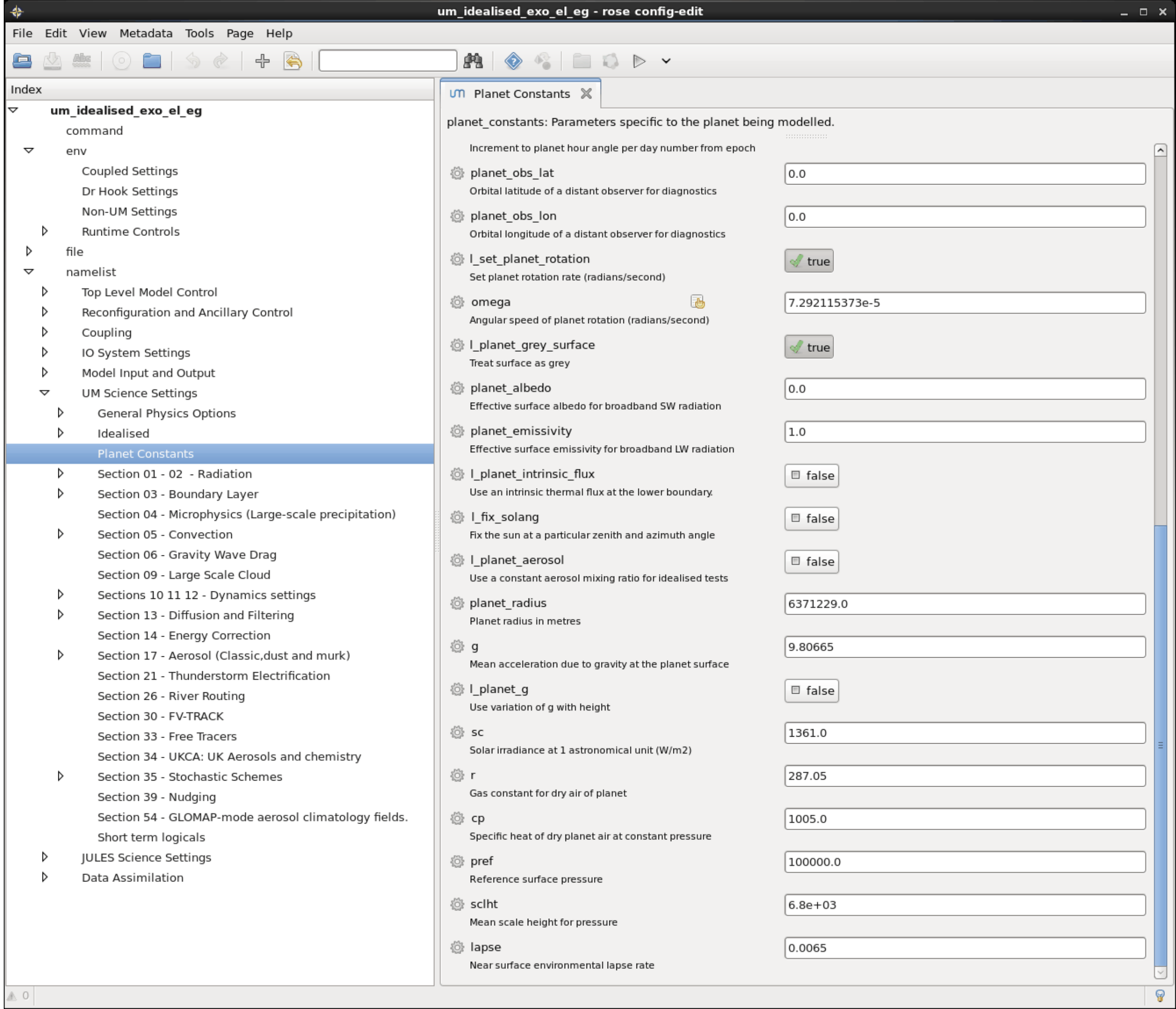
planet_dha — Increment to planet hour angle per day number from epoch: 6.283185307179586

planet_obs_lat — Orbital latitude of a distant observer for diagnostics: 0.0

planet_obs_lon — Orbital longitude of a distant observer for diagnostics: 0.0

l_set_planet_rotation — Set planet rotation rate (radians/second): ✓ true

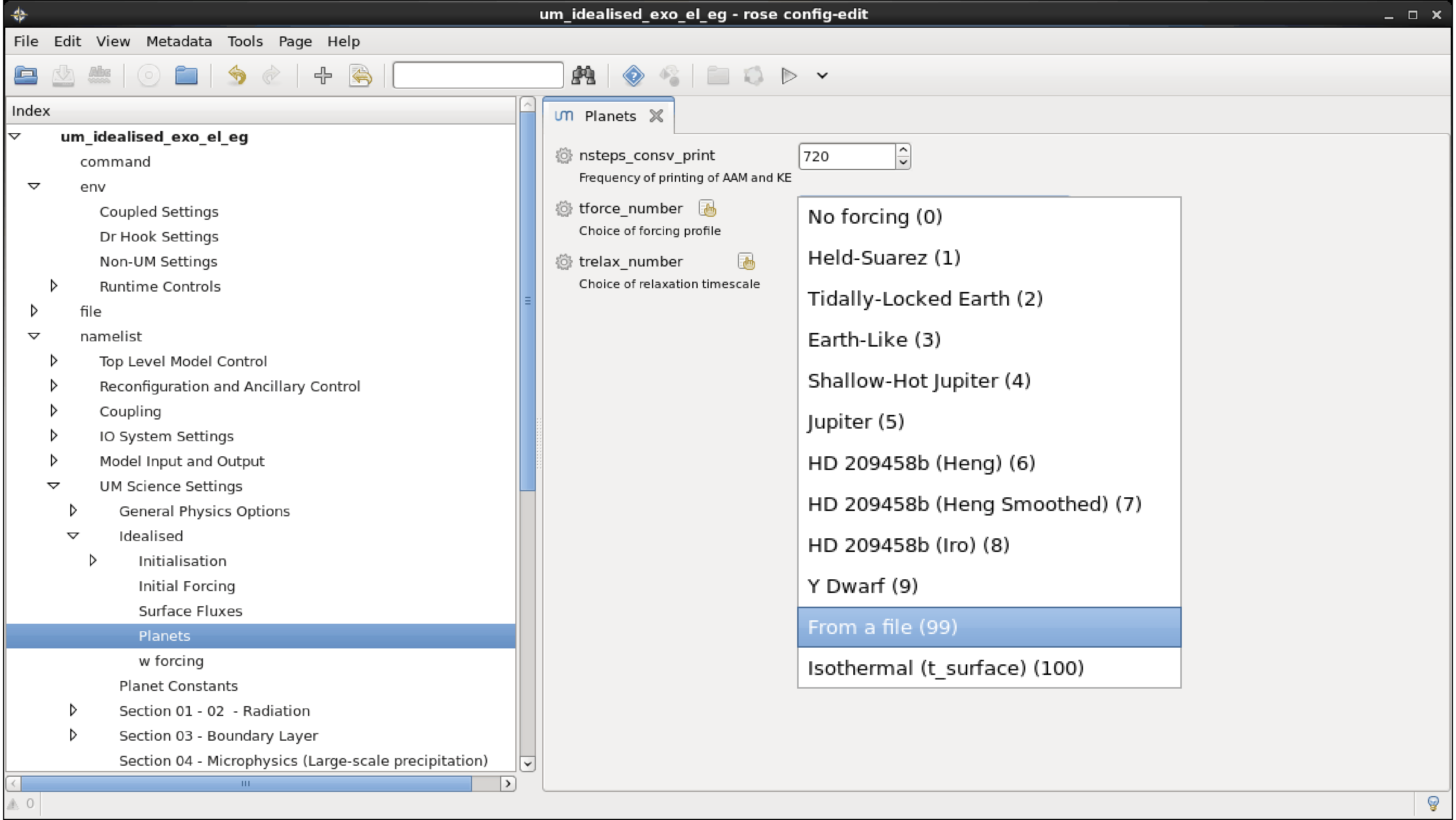
Planet parameters



planet_constants: Parameters specific to the planet being modelled.

Increment to planet hour angle per day number from epoch

planet_obs_lat Orbital latitude of a distant observer for diagnostics	0.0
planet_obs_lon Orbital longitude of a distant observer for diagnostics	0.0
l_set_planet_rotation Set planet rotation rate (radians/second)	✓ true
omega Angular speed of planet rotation (radians/second)	7.292115373e-5
l_planet_grey_surface Treat surface as grey	✓ true
planet_albedo Effective surface albedo for broadband SW radiation	0.0
planet_emissivity Effective surface emissivity for broadband LW radiation	1.0
l_planet_intrinsic_flux Use an intrinsic thermal flux at the lower boundary.	☐ false
l_fix_solang Fix the sun at a particular zenith and azimuth angle	☐ false
l_planet_aerosol Use a constant aerosol mixing ratio for idealised tests	☐ false
planet_radius Planet radius in metres	6371229.0
g Mean acceleration due to gravity at the planet surface	9.80665
l_planet_g Use variation of g with height	☐ false
sc Solar irradiance at 1 astronomical unit (W/m2)	1361.0
r Gas constant for dry air of planet	287.05
cp Specific heat of dry planet air at constant pressure	1005.0
pref Reference surface pressure	100000.0
sclht Mean scale height for pressure	6.8e+03
lapse Near surface environmental lapse rate	0.0065



um_idealised_exo_el_eg - rose config-edit

nsteps_consv_print 720

Frequency of printing of AAM and KE

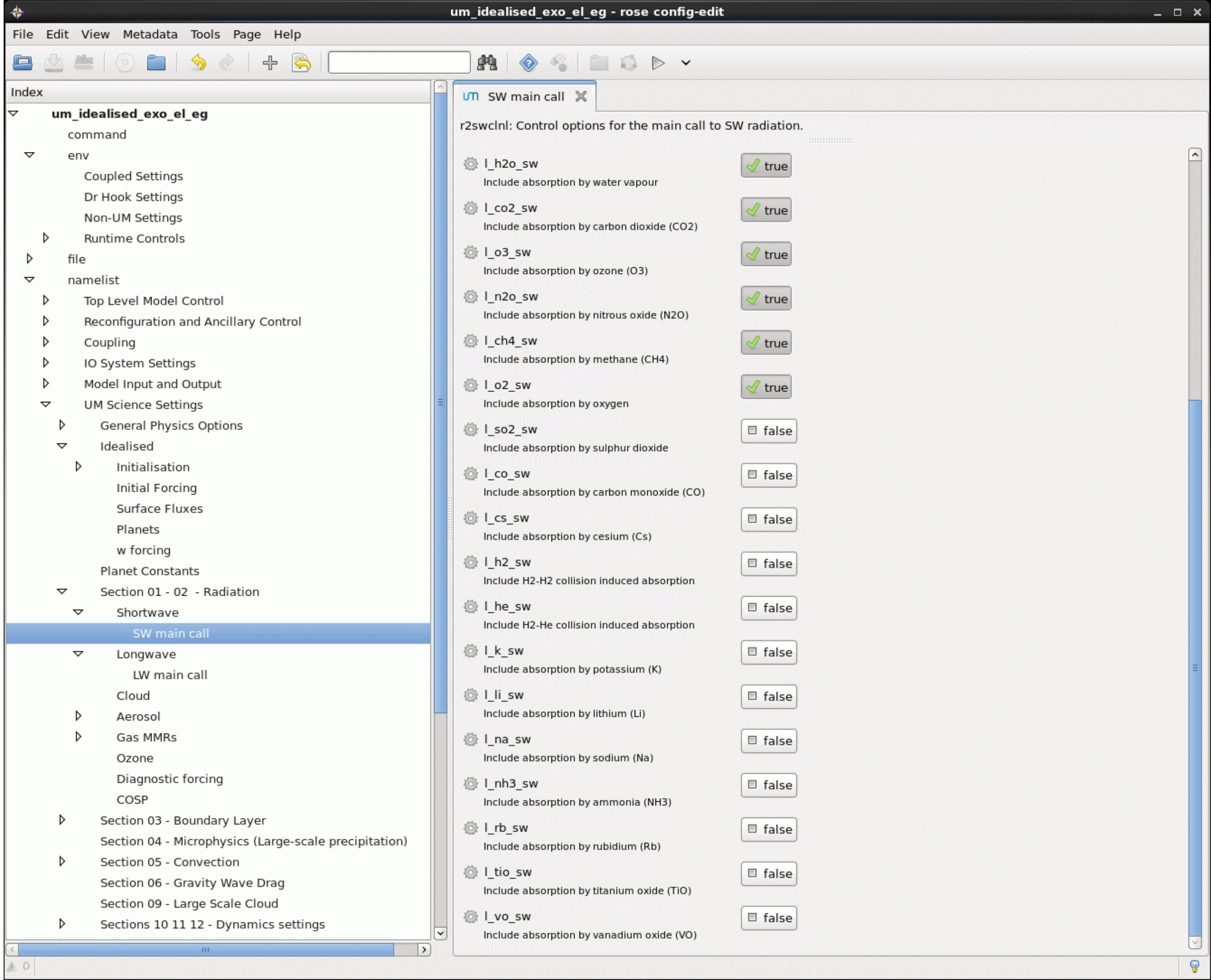
tforce_number

Choice of forcing profile

trelax_number

Choice of relaxation timescale

Exotic gas species



r2swclnl: Control options for the main call to SW radiation.

l_h2o_sw ✓ true
Include absorption by water vapour

l_co2_sw ✓ true
Include absorption by carbon dioxide (CO2)

l_o3_sw ✓ true
Include absorption by ozone (O3)

l_n2o_sw ✓ true
Include absorption by nitrous oxide (N2O)

l_ch4_sw ✓ true
Include absorption by methane (CH4)

l_o2_sw ✓ true
Include absorption by oxygen

l_so2_sw ☐ false
Include absorption by sulphur dioxide

l_co_sw ☐ false
Include absorption by carbon monoxide (CO)

l_cs_sw ☐ false
Include absorption by cesium (Cs)

l_h2_sw ☐ false
Include H2-H2 collision induced absorption

l_he_sw ☐ false
Include H2-He collision induced absorption

l_k_sw ☐ false
Include absorption by potassium (K)

l_li_sw ☐ false
Include absorption by lithium (Li)

l_na_sw ☐ false
Include absorption by sodium (Na)

l_nh3_sw ☐ false
Include absorption by ammonia (NH3)

l_rb_sw ☐ false
Include absorption by rubidium (Rb)

l_tio_sw ☐ false
Include absorption by titanium oxide (TiO)

l_vo_sw ☐ false
Include absorption by vanadium oxide (VO)

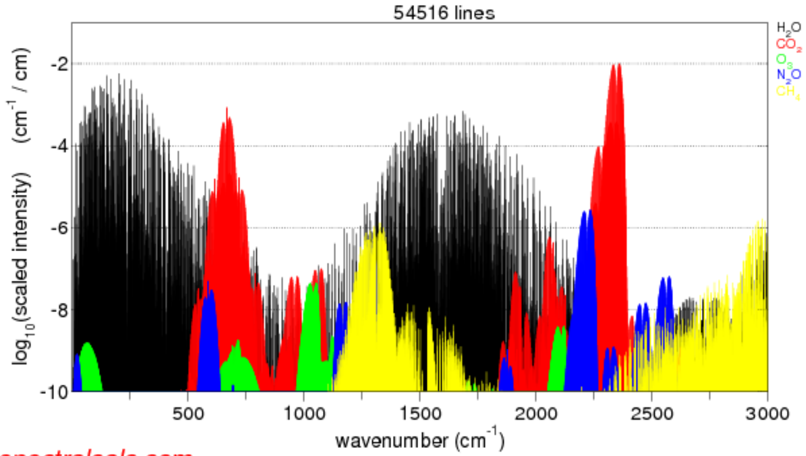
Flexible configuration: spectral files

Spectral bands: high / low resolution

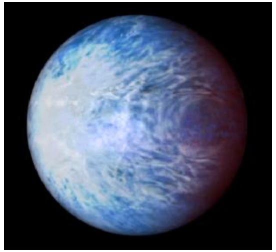
Gas *k*-terms

Aerosol / cloud optical properties

Solar spectrum (including time variation) etc.



spectralcalc.com



Hot Jupiters

Mars

Many configurations can be run

HadCM3

HadGEM1

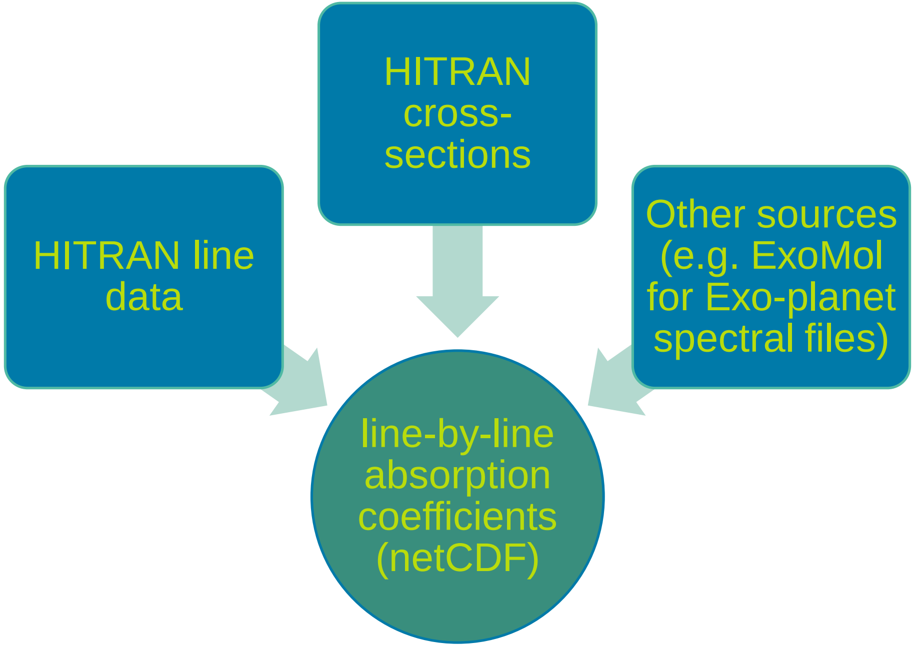
HadGEM2

GA3

GA7

300 band LW / 260 band SW

Stage 1:
generate line-by-line absorption coefficients



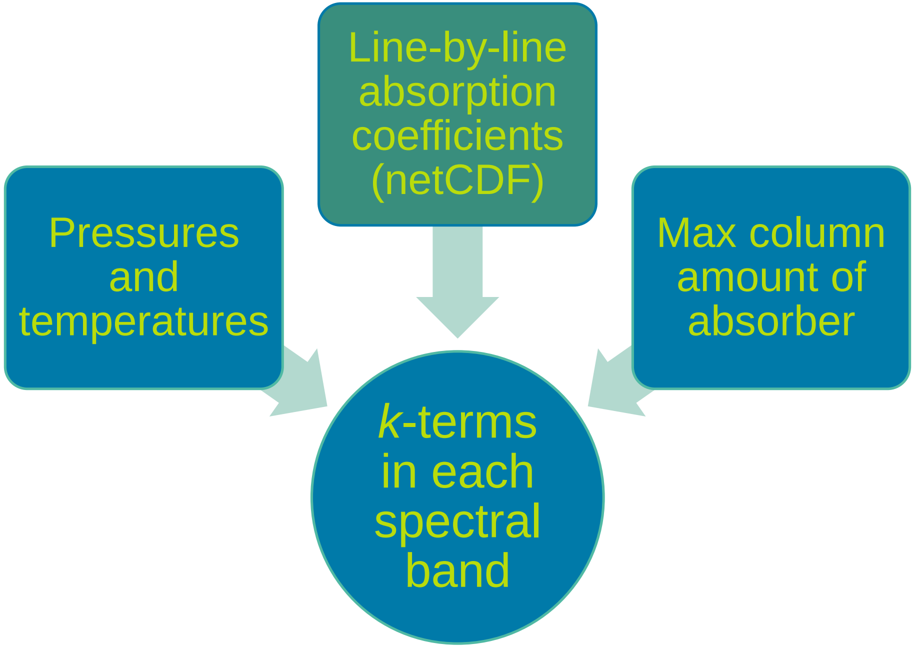
HITRAN cross-sections

HITRAN line data

Other sources (e.g. ExoMol for Exo-planet spectral files)

line-by-line absorption coefficients (netCDF)

Stage 2:
generate k-terms separately for each gas



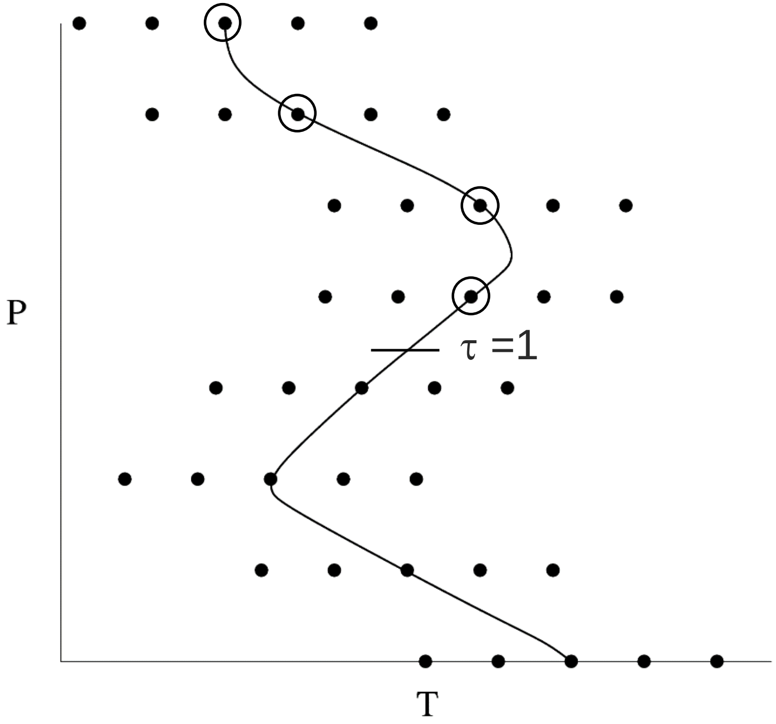
Line-by-line absorption coefficients (netCDF)

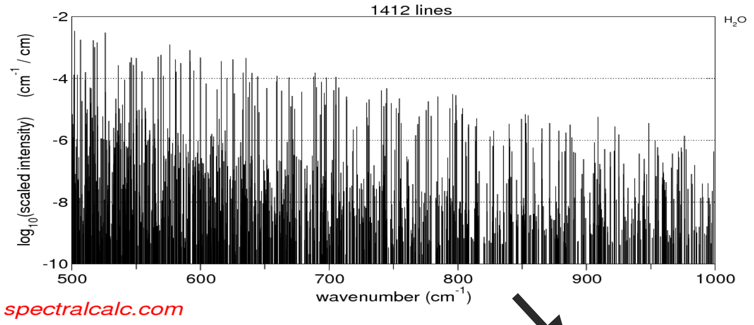
Pressures and temperatures

Max column amount of absorber

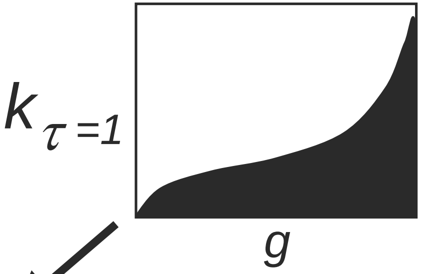
k-terms in each spectral band

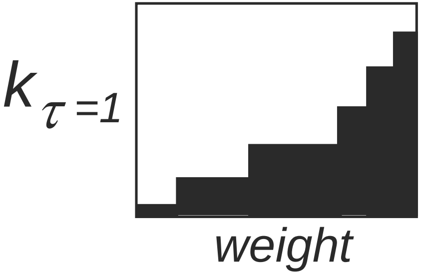
Optimal selection of k-term weights





Effective absorption coefficient for column down to τ=1

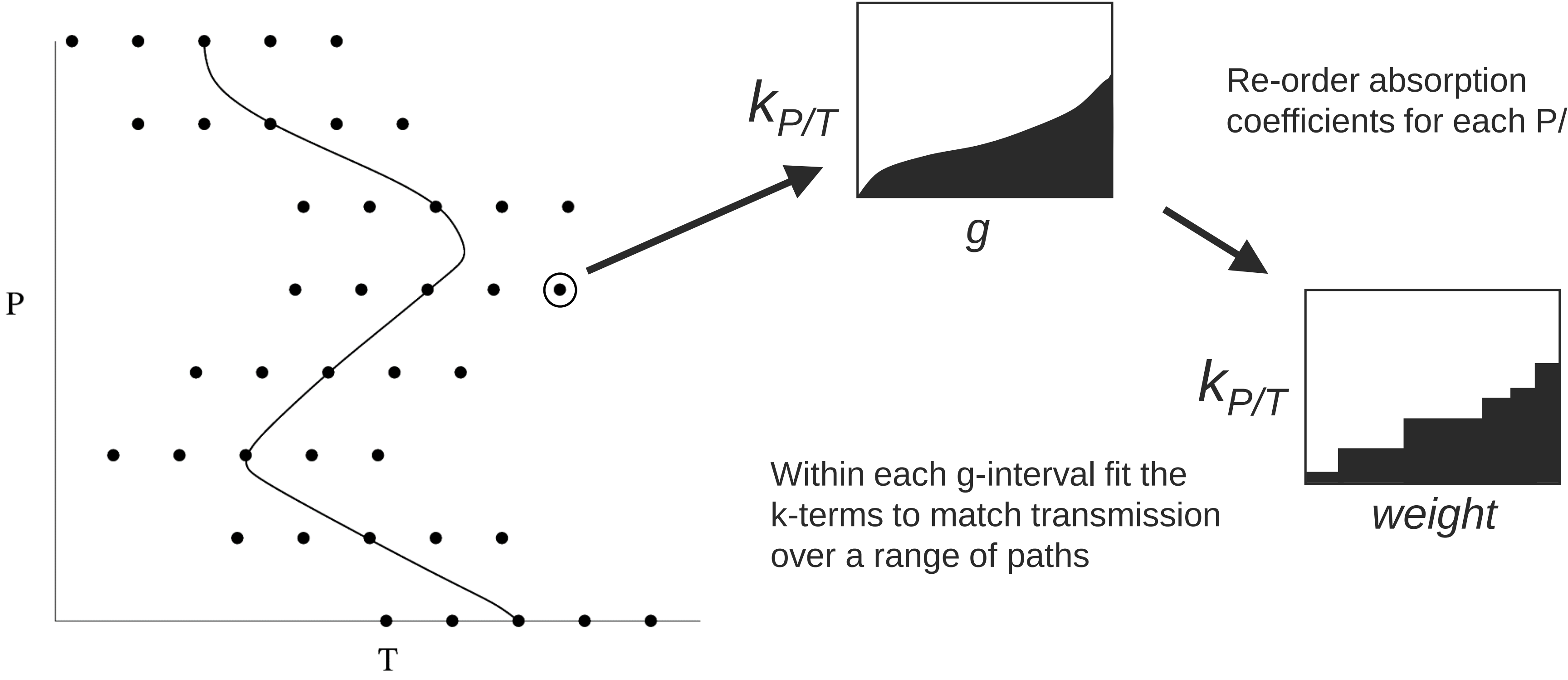




Use weights that give equal increments in log $k_{\tau=1}$

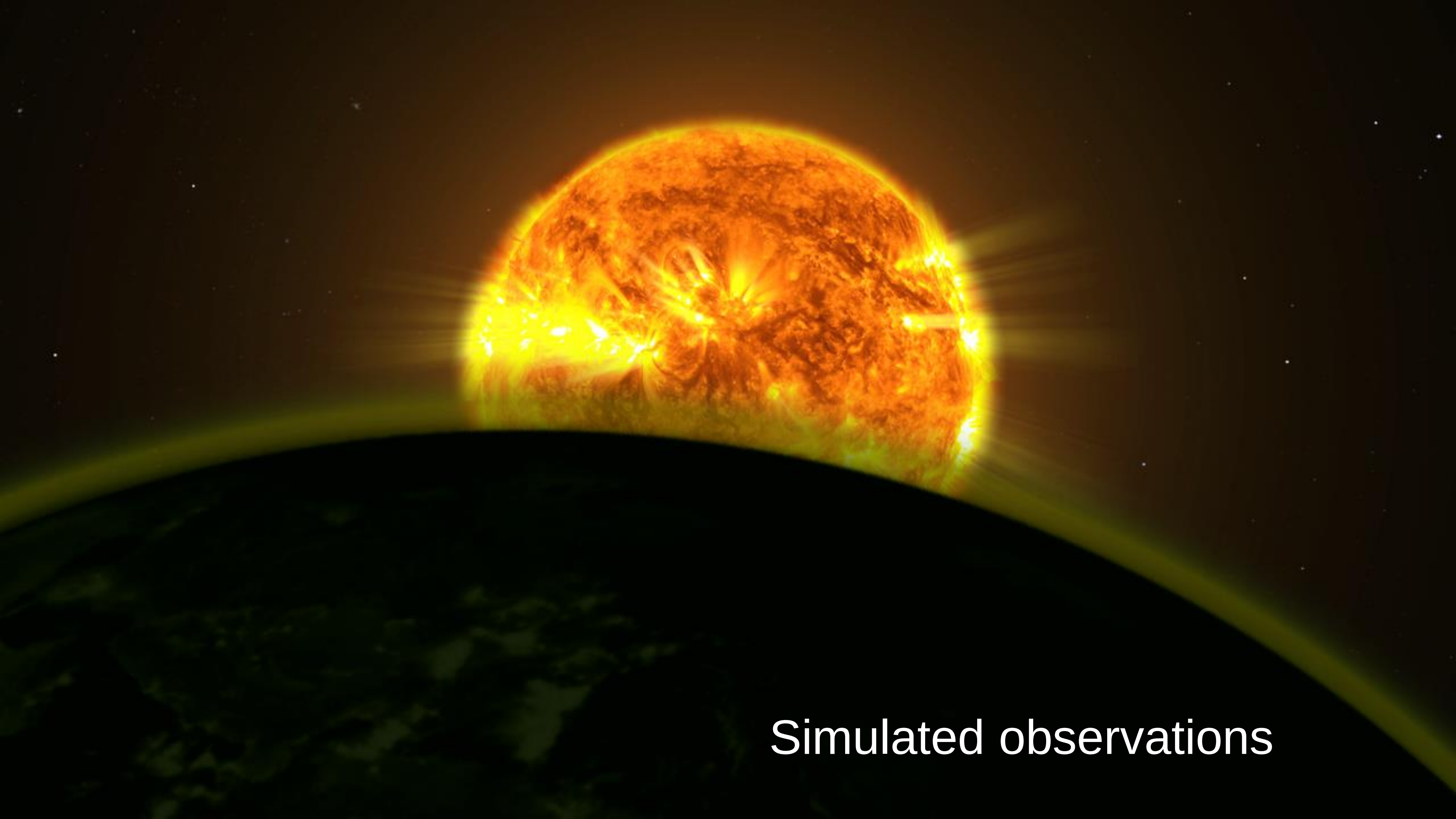
(Based on similar ideas from Hogan 2010)

Calculate k-terms for P/T look-up table



Re-order absorption coefficients for each P/T

Within each g-interval fit the k-terms to match transmission over a range of paths



Simulated observations

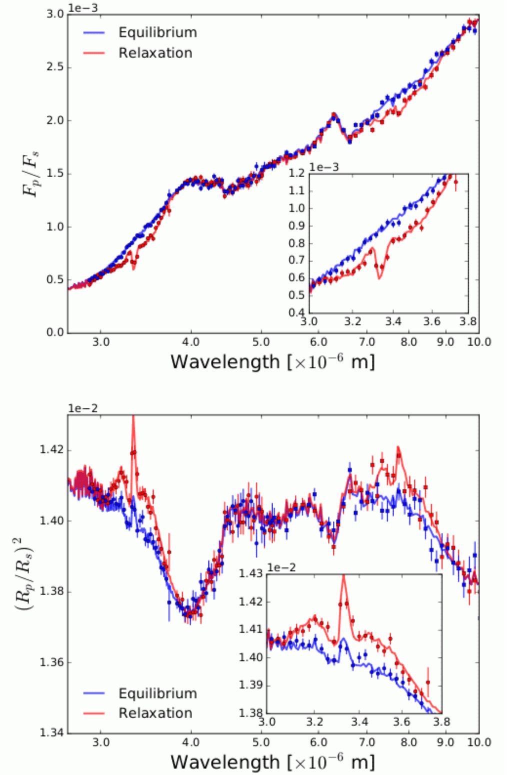
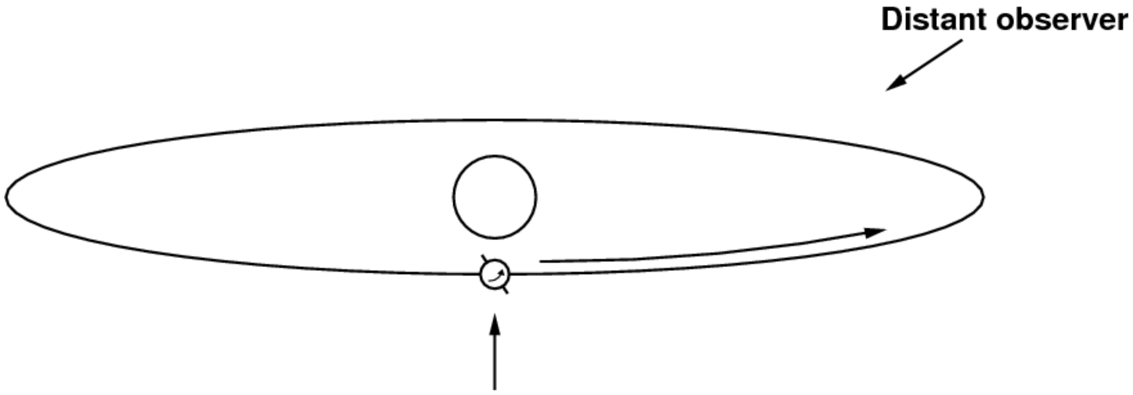
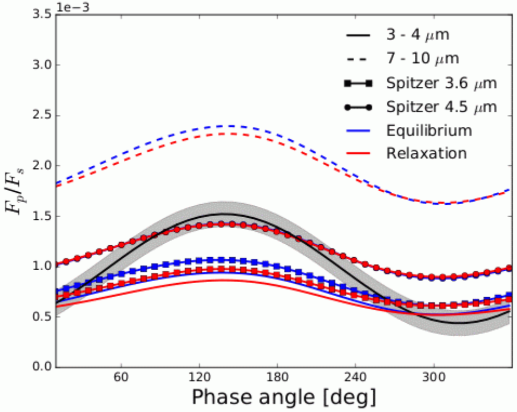


Figure 5. *Top*: emission phase curves in several spectral bands. The observed 4.5 µm *Spitzer*/IRAC channel curve (Zellem et al. 2014) is included (black) with 1σ uncertainty. *Middle and Bottom*: secondary eclipse emission and transmission spectra with PandExo simulated observations for the NIRSpec G395H (circles) and MIRI LRS (squares) modes, binned to a resolution of $R \sim 60$ and $R \sim 30$, respectively.



Distant observer

Distant transit observer



Simulated observations

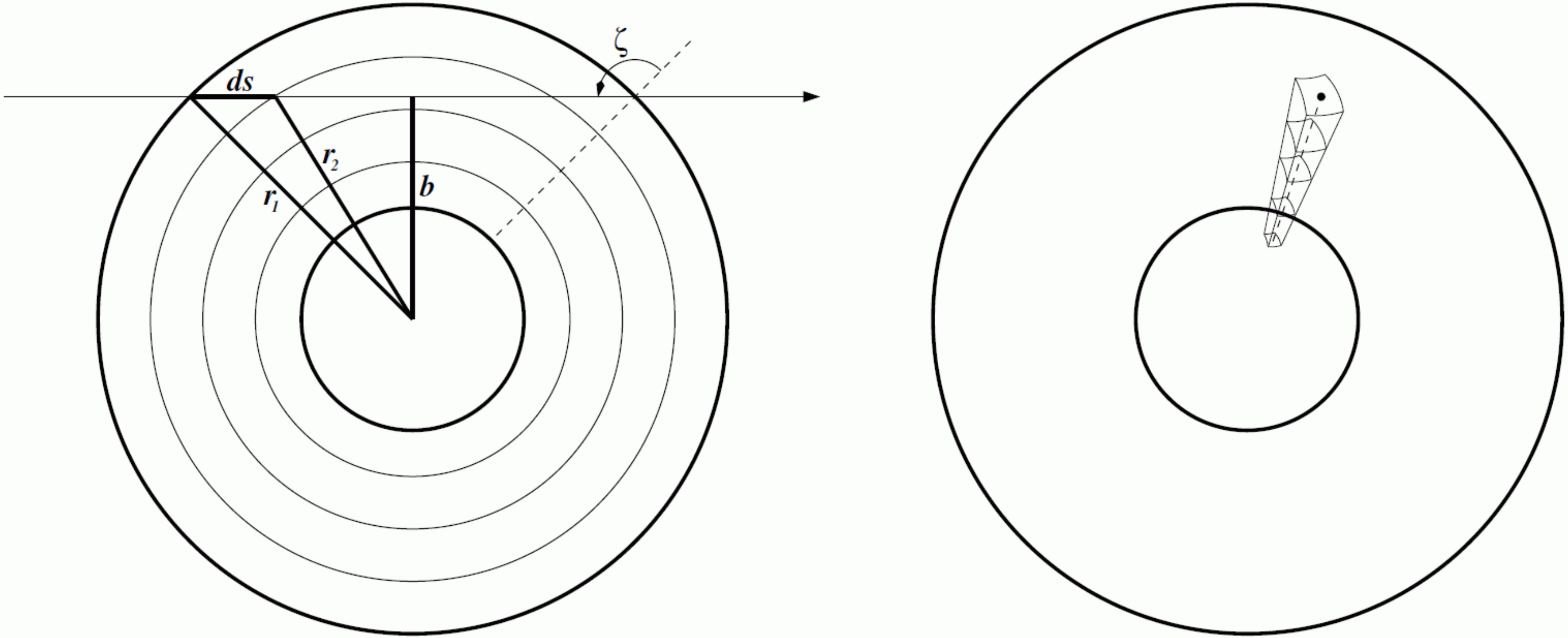


Fig. 1: Spherical shell geometry used for the calculation of transmission spectra. Left-hand plot (a) shows the view perpendicular to the transit. Right-hand plot (b) shows the view from the night side in line with the transit. Parameters are shown for a model column located in the position of the dotted line in each plot, giving a transmission spectrum at the point where the arrow leaves the top of the atmosphere (indicated by the dot in the right-hand plot). ζ denotes the stellar zenith angle, b the impact parameter, and ds the path length element for the layer bounded by radii r_1 and r_2. Note the path of the beam will pass through each layer twice, except for the layer in which the impact parameter is found.

Spherical geometry for SW heating

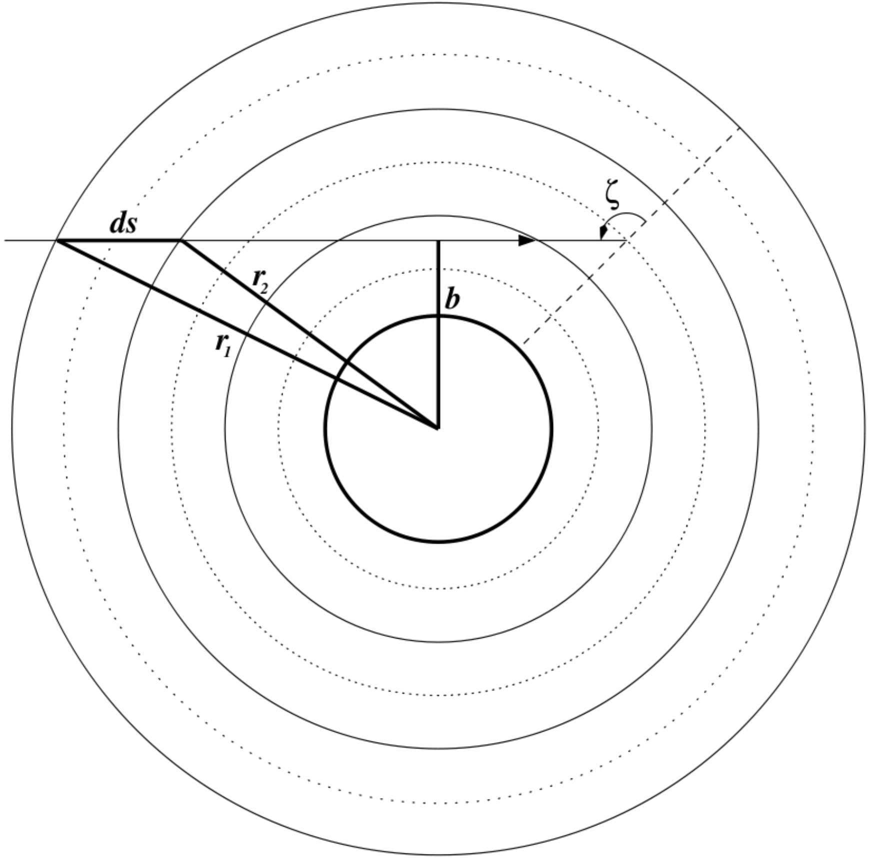
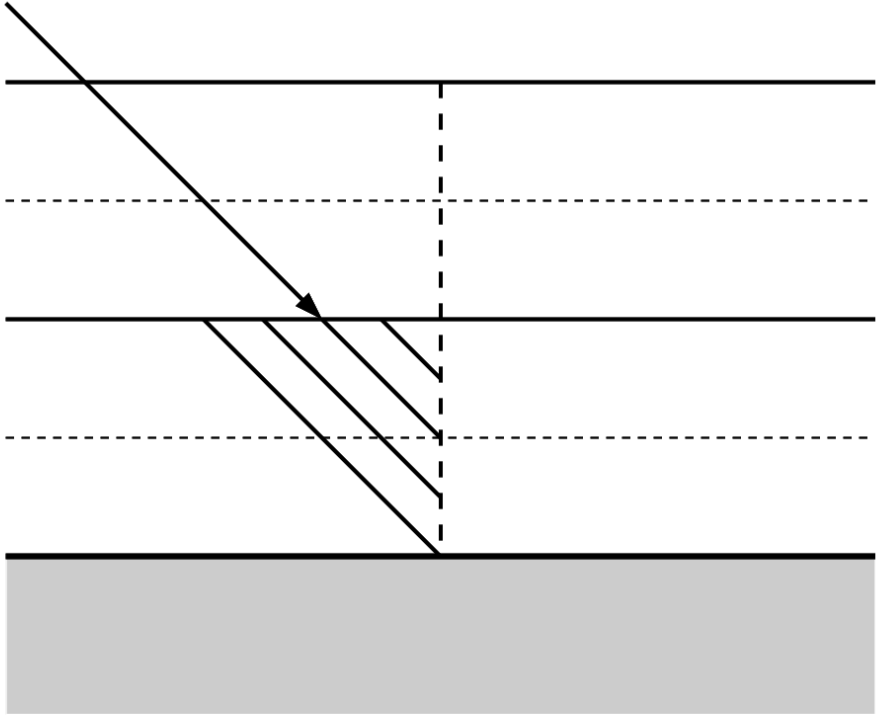
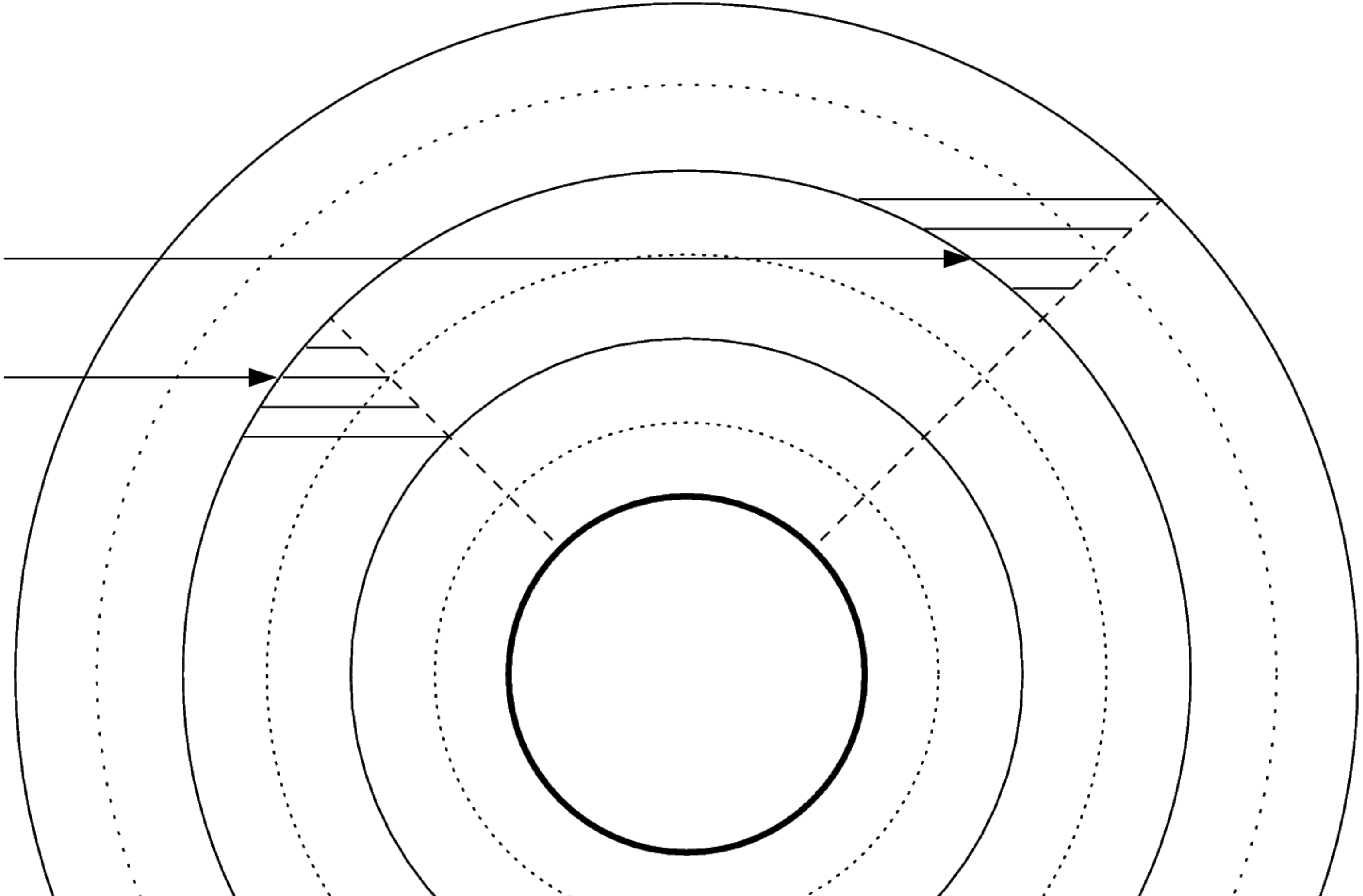
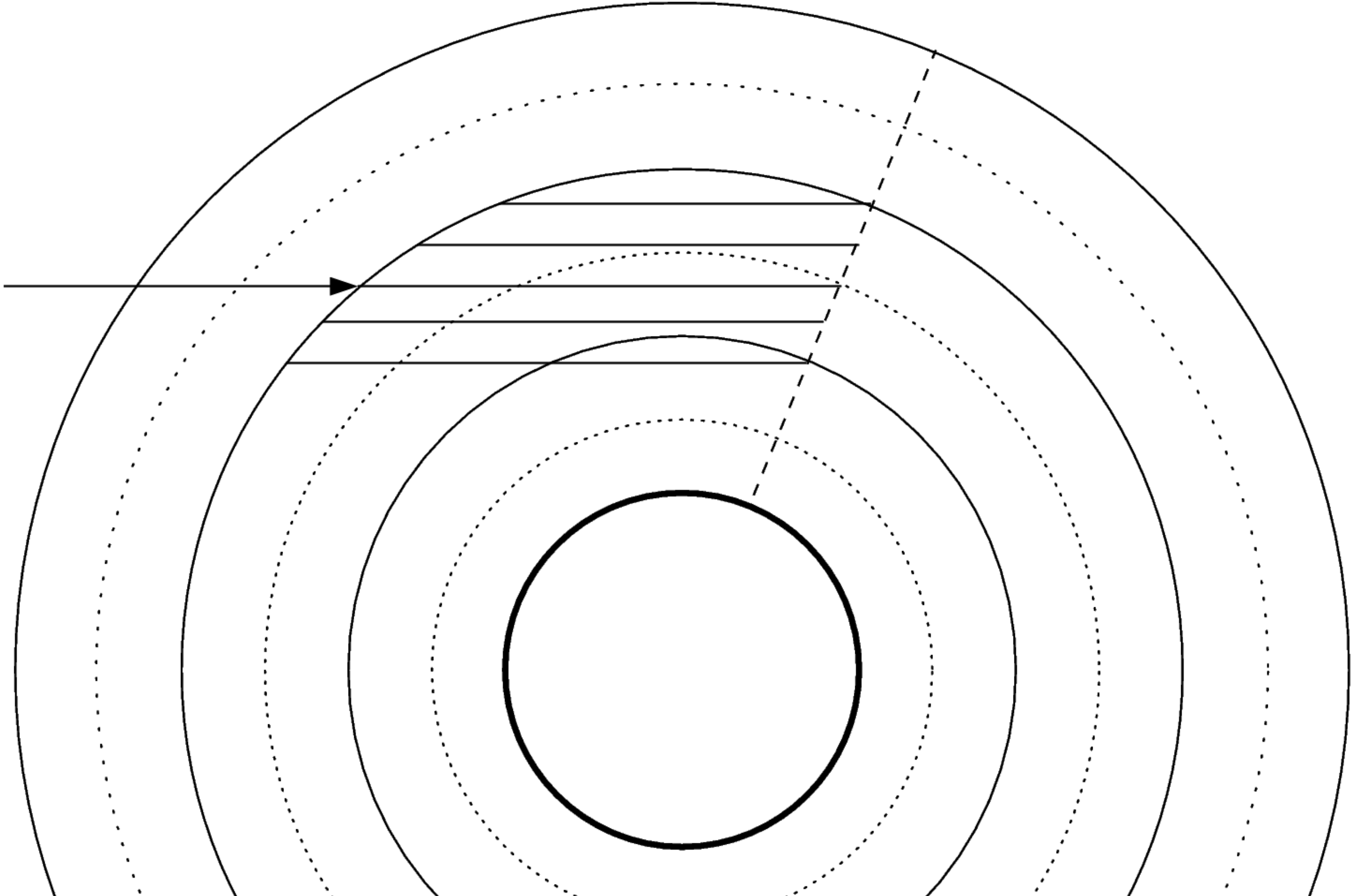
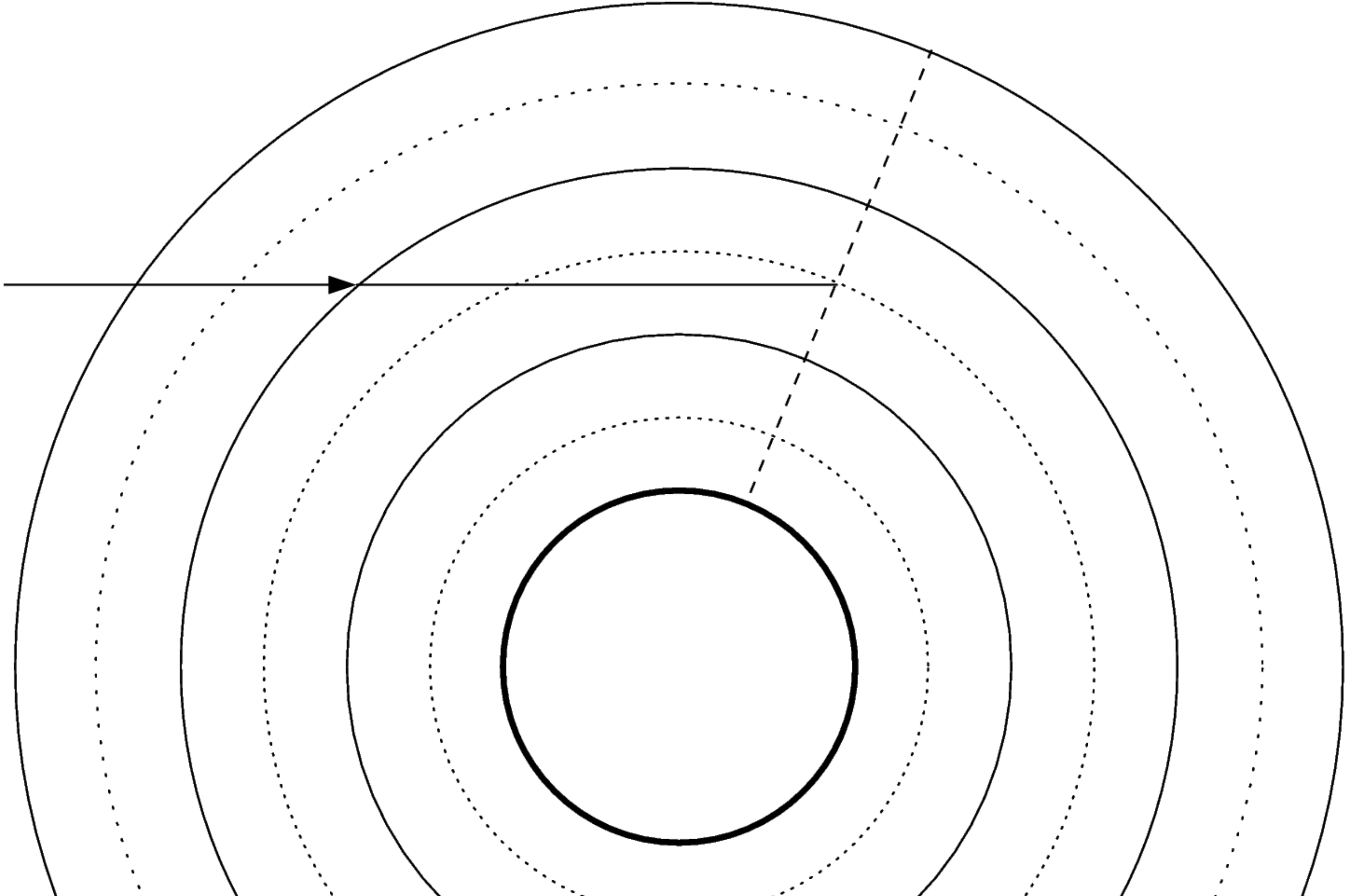


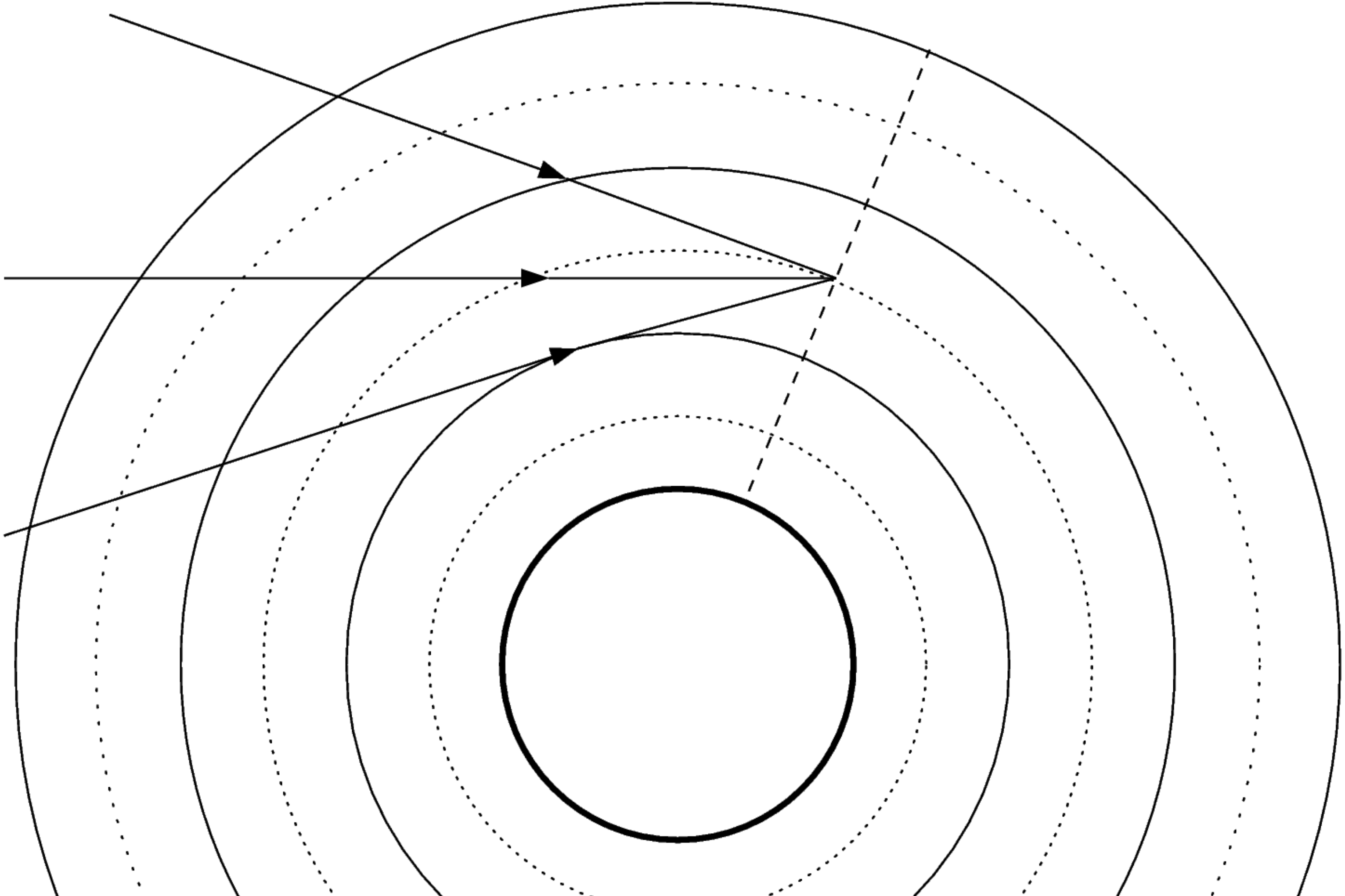
Figure 1.2: Spherical shell geometry. Layer centres are denoted by dotted lines and layer edges by solid lines. Parameters are shown for the slant path to a particular layer for a model column located in the position of the dashed line. ζ denotes the local solar zenith angle (which may be greater than 90 degrees), b the impact parameter, and ds the path length element for the layer bounded by radii r_1 and r_2.

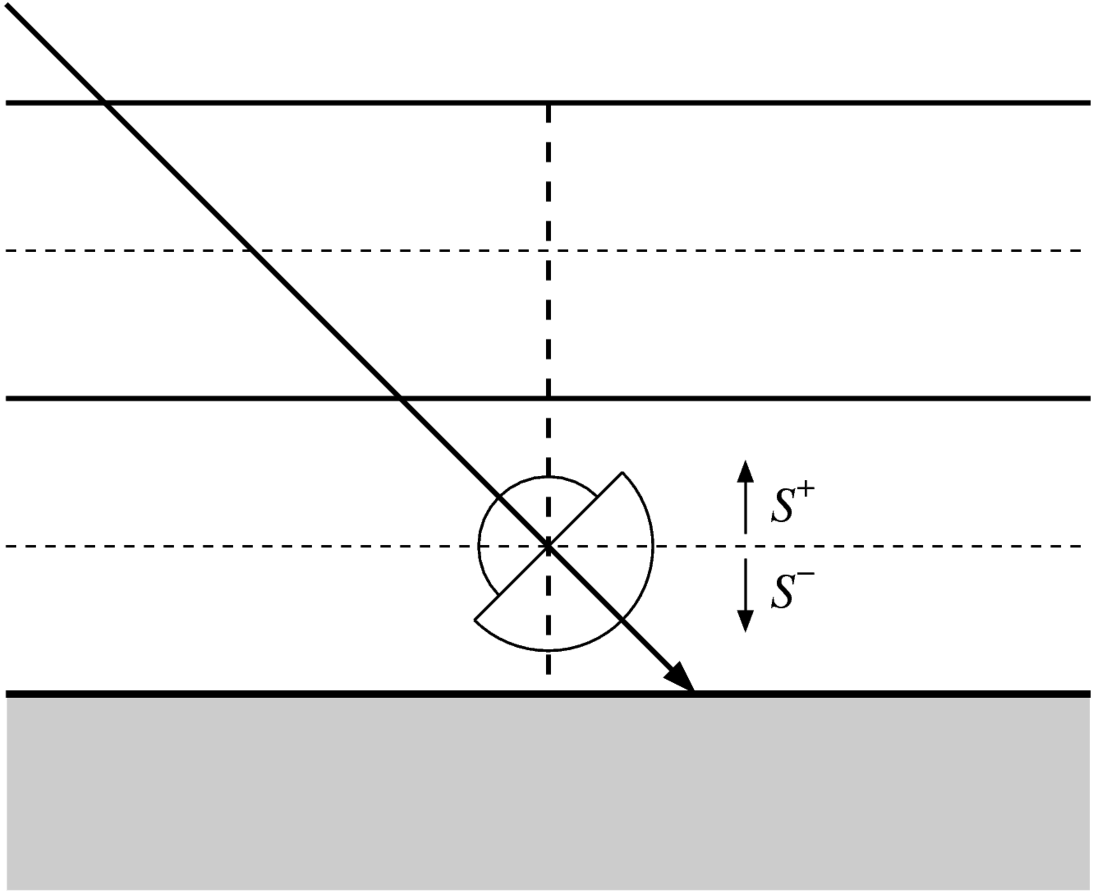






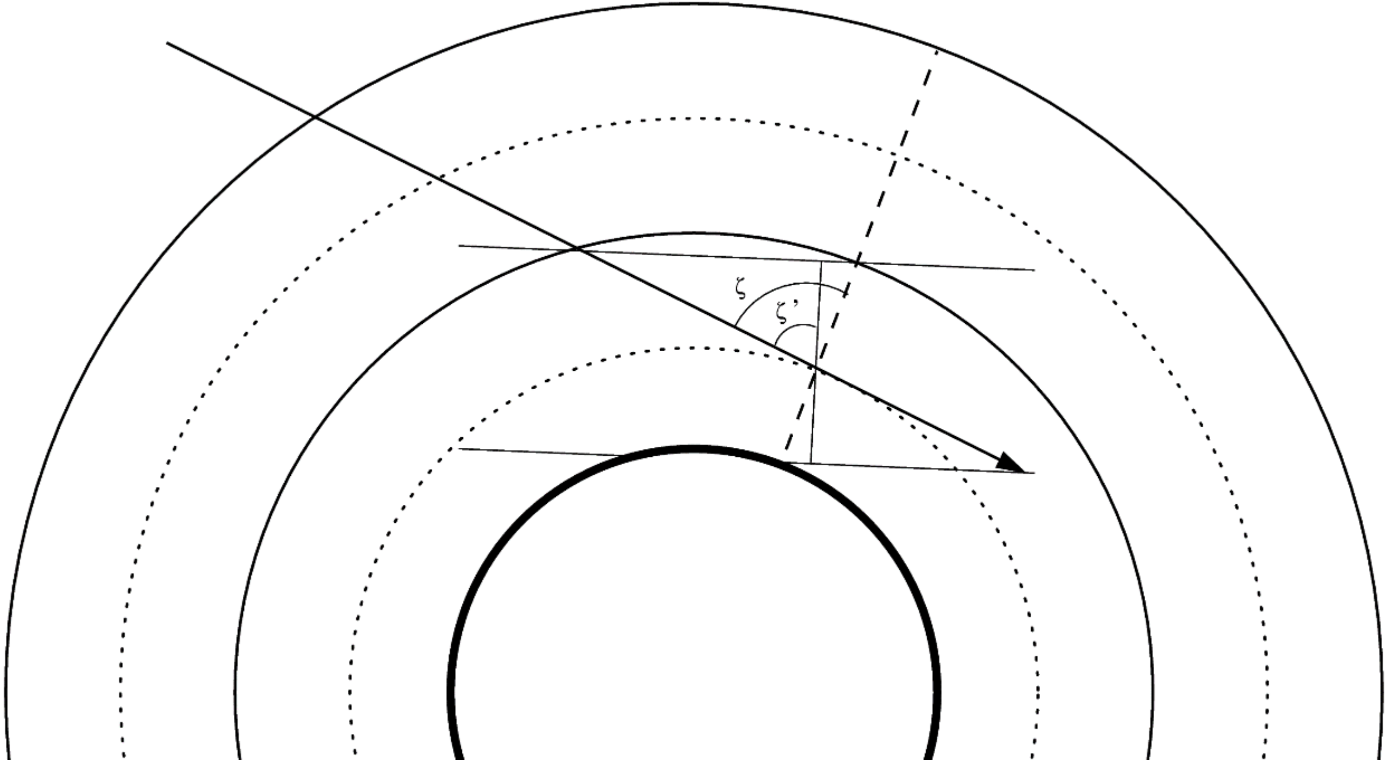


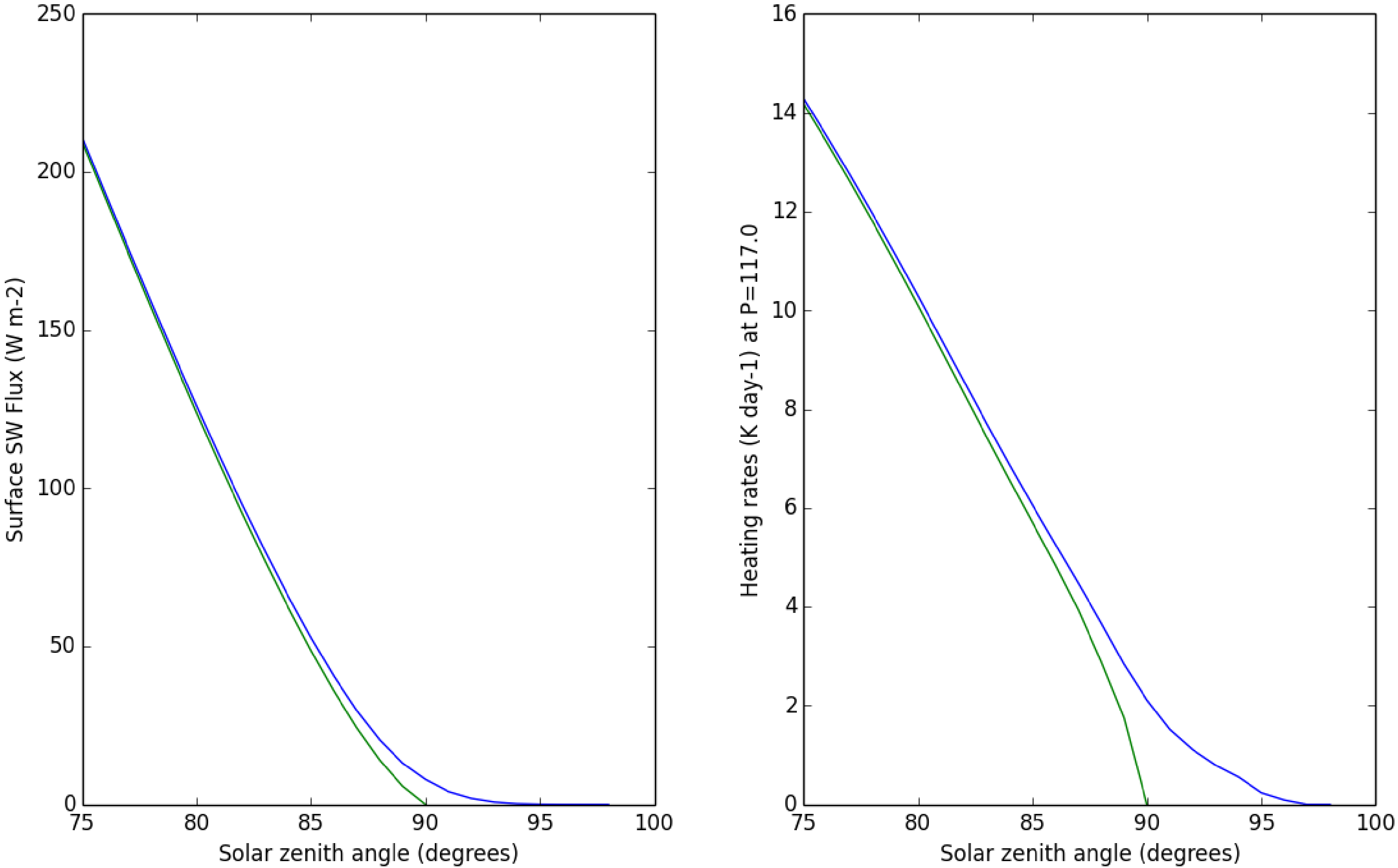



S^+
S^-

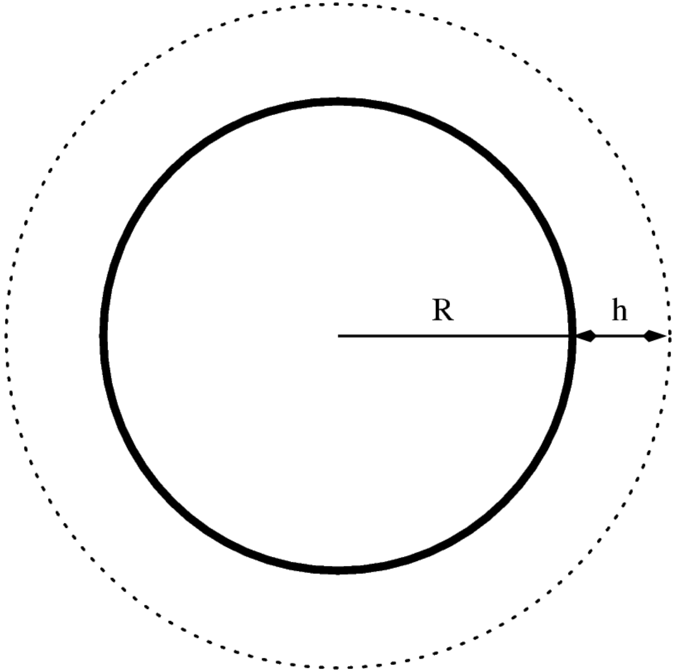
$$S_{up} = \frac{1}{2}[(1+\cos\zeta\sec\zeta')S'^{+} + (1-\cos\zeta\sec\zeta')S'^{-}]$$

$$S_{down} = \frac{1}{2}[(1+\cos\zeta\sec\zeta')S'^{-} + (1-\cos\zeta\sec\zeta')S'^{+}]$$




Surface SW Flux (W m-2)
250
200
150
100
50
0
75
80
85
90
95
100
Solar zenith angle (degrees)
Heating rates (K day-1) at P=117.0
16
14
12
10
8
6
4
2
0
75
80
85
90
95
100
Solar zenith angle (degrees)

Energy balance



h ~ 1% of R

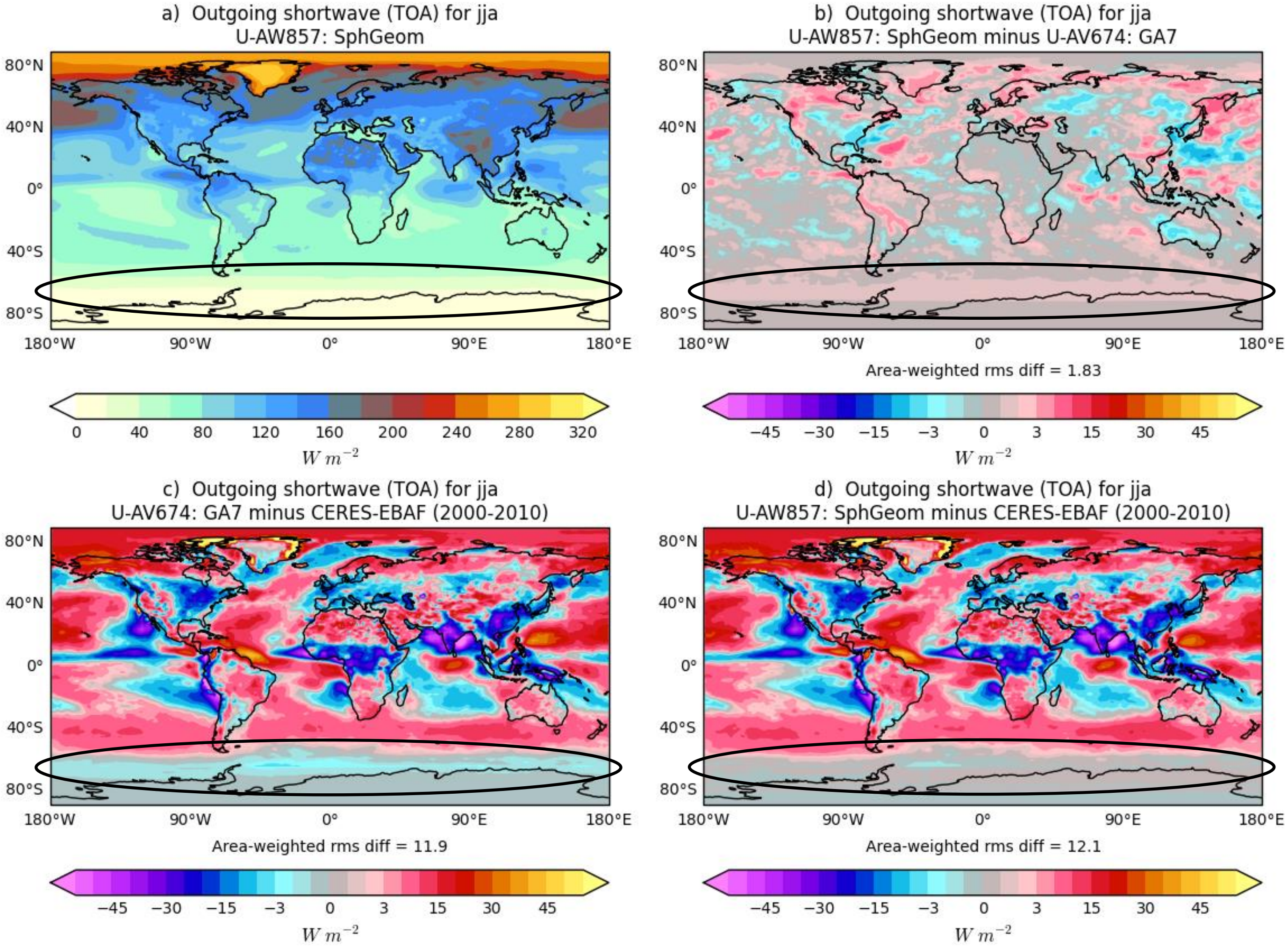
Area increase ~ 2%

Tropopause lit ~450km into nightside
(an extra 30 minutes daylight)

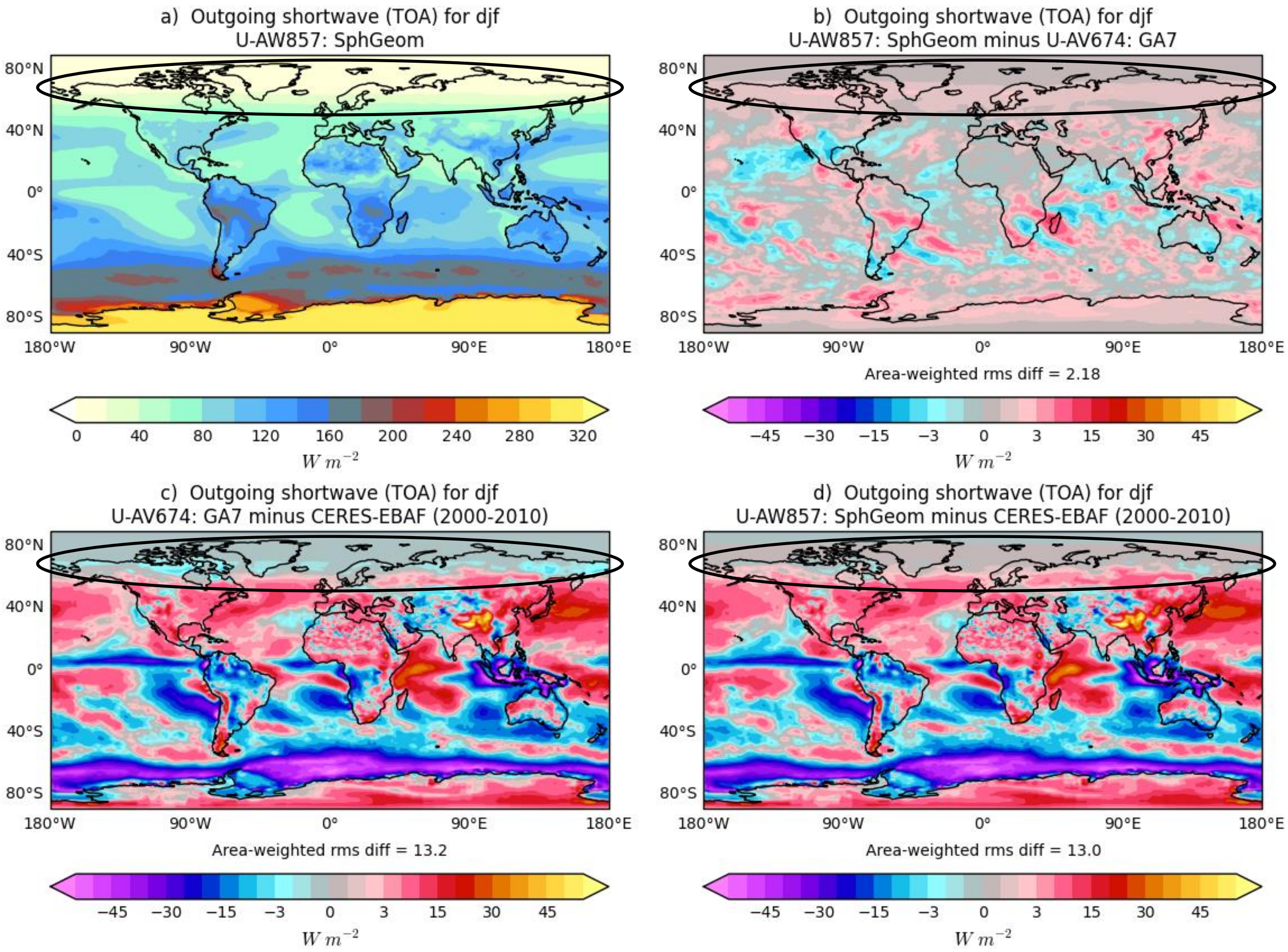
Surface area for emission should also increase (to be done)

20-year climate run

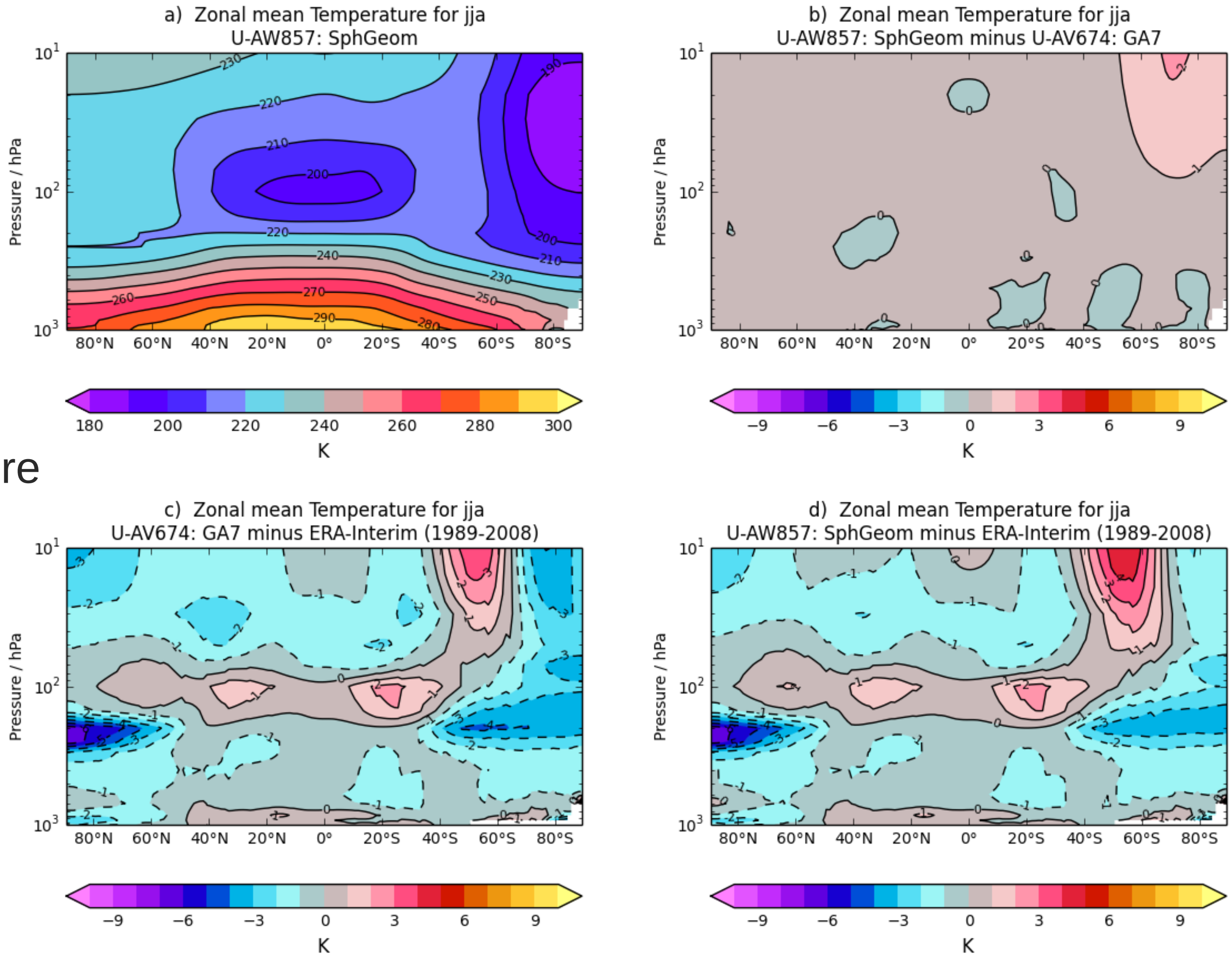
Outgoing SW at TOA
June-July-August



Outgoing SW at TOA
Dec-Jan-Feb



Zonal mean Temperature
June-July-August



a) Zonal mean Temperature for jja
U-AW857: SphGeom

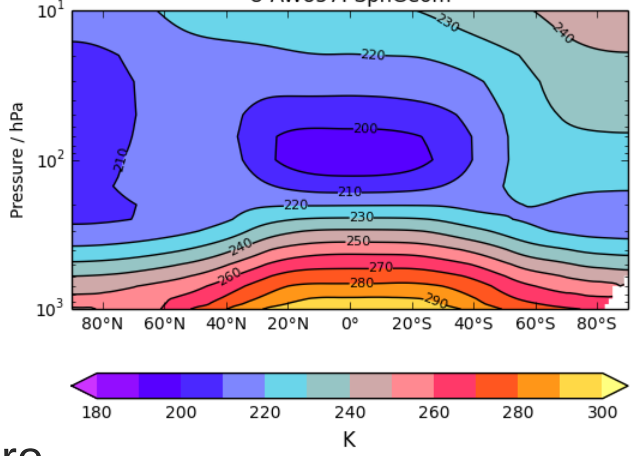
b) Zonal mean Temperature for jja
U-AW857: SphGeom minus U-AV674: GA7

c) Zonal mean Temperature for jja
U-AV674: GA7 minus ERA-Interim (1989-2008)

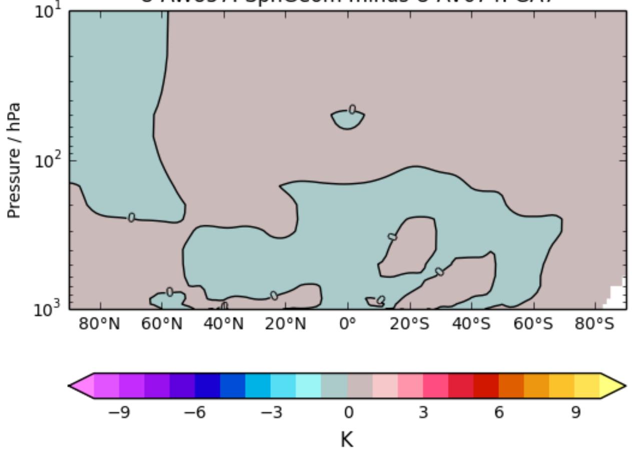
d) Zonal mean Temperature for jja
U-AW857: SphGeom minus ERA-Interim (1989-2008)

Zonal mean Temperature
Dec-Jan-Feb

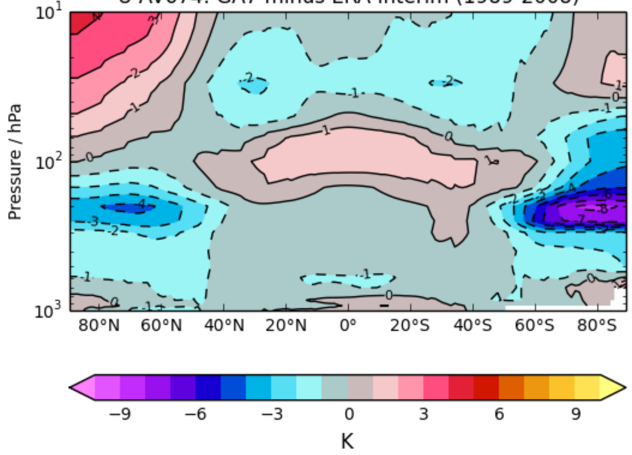
a) Zonal mean Temperature for djf
U-AW857: SphGeom



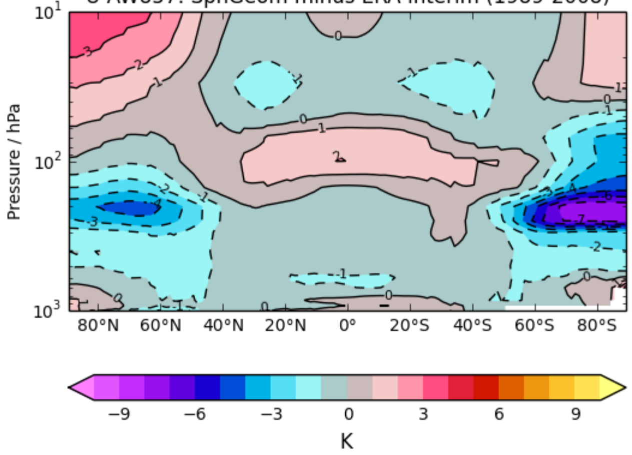
b) Zonal mean Temperature for djf
U-AW857: SphGeom minus U-AV674: GA7



c) Zonal mean Temperature for djf
U-AV674: GA7 minus ERA-Interim (1989-2008)



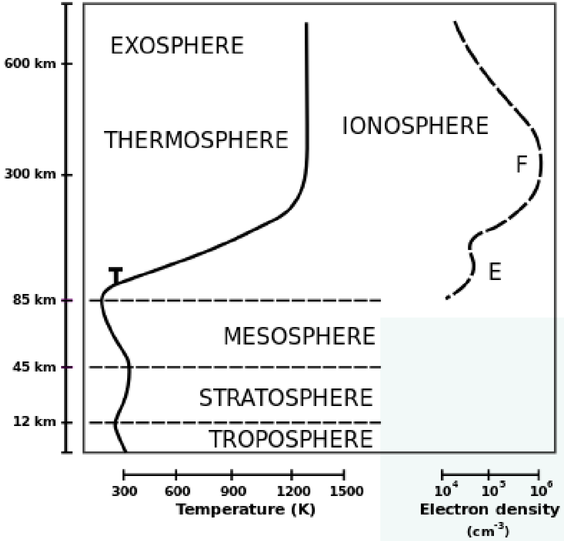
d) Zonal mean Temperature for djf
U-AW857: SphGeom minus ERA-Interim (1989-2008)



Future enhancements and uses of this scheme:

- spherical treatment for diffuse fluxes needed for energy balance
- different cloud overlap for slant path to each layer
- orography can cast shadows into the atmosphere
- photolysis in upper atmosphere

Photolysis and heating in the upper atmosphere



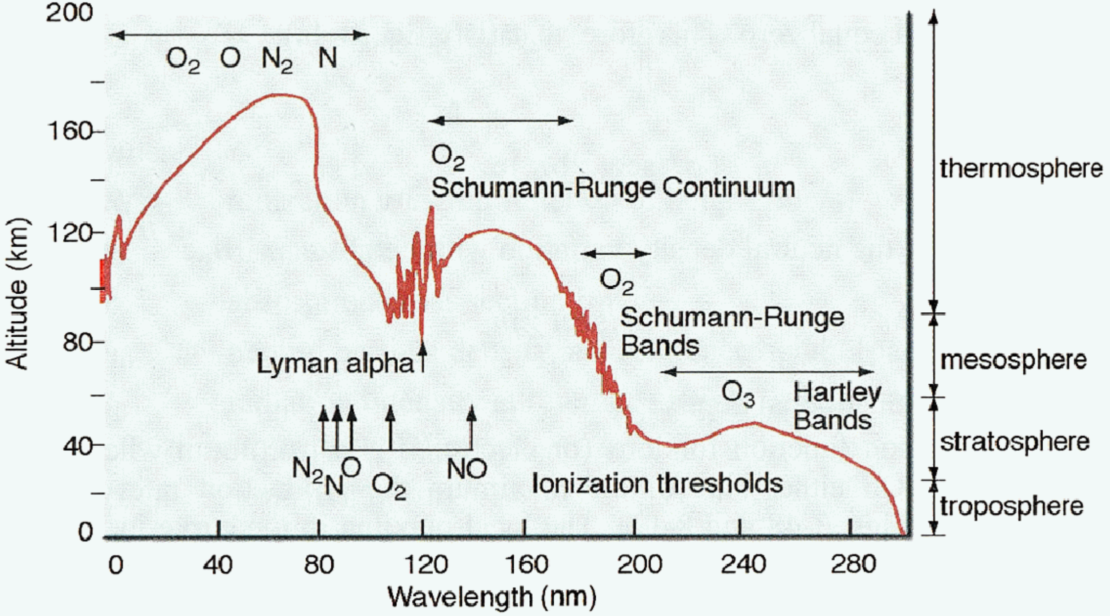
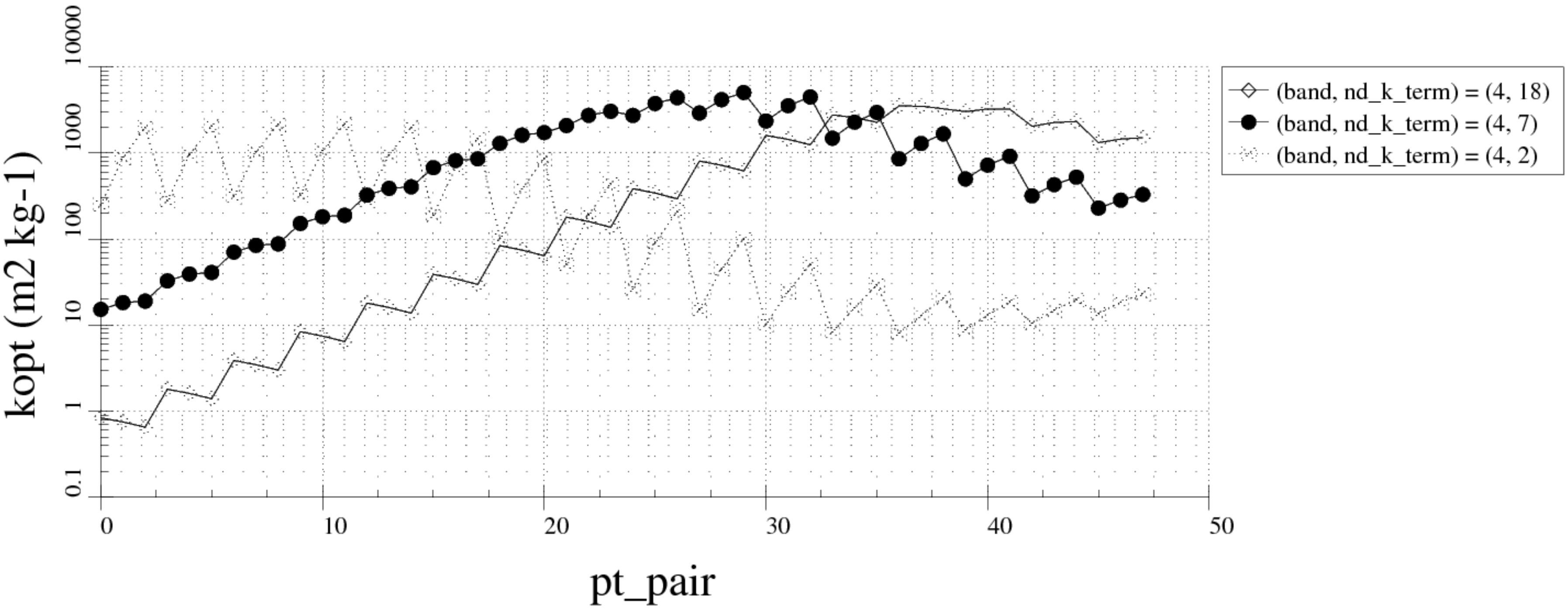


Fig. 5 Solar irradiance atmospheric penetration depth, unitary optical depth, for photons from hard X-rays to 300 nm (from Chamberlain 1978)

Questions

1	☐ 2018arXiv180300226L	1.000	03/2018	A		X	R		U
	Lines, S.; Mayne, N. J.; Boutle, Ian A.; Manners, James; Lee, Graham K. H.; Helling, Ch.; Drummond, Benjamin; Amundsen, David S.; Goyal, Jayesh; Acreman, David M.; and 2 coauthors	Simulating the cloudy atmospheres of HD 209458 b and HD 189733 b with the 3D Met Office Unified Model							
2	☐ 2018arXiv180209222D	1.000	02/2018	A		X	R		U
	Drummond, Benjamin; Mayne, N. J.; Manners, James; Carter, Aarynn L.; Boutle, Ian A.; Baraffe, Isabelle; Hebrard, Eric; Tremblin, Pascal; Sing, David K.; Amundsen, David S.; Acreman, Dave	Observable signatures of wind--driven chemistry with a fully consistent three dimensional radiative hydrodynamics model of HD 209458b							
3	☐ 2018ApJ...854..171L	1.000	02/2018	A	E F	X	R		U
	Lewis, Neil T.; Lambert, F. Hugo; Boutle, Ian A.; Mayne, Nathan J.; Manners, James; Acreman, David M.	The Influence of a Substellar Continent on the Climate of a Tidally Locked Exoplanet							
4	☐ 2018arXiv180101045D	1.000	01/2018	A		X	R		U
	Drummond, Benjamin; Mayne, N. J.; Baraffe, Isabelle; Tremblin, Pascal; Manners, James; Amundsen, David S.; Goyal, Jayesh; Acreman, Dave	The effect of metallicity on the atmospheres of exoplanets with fully coupled 3D hydrodynamics, equilibrium chemistry, and radiative transfer							
5	☐ 2017A&A...604A..79M	1.000	08/2017	A	E F	X	R C	S	U
	Mayne, Nathan J.; Debras, Florian; Baraffe, Isabelle; Thuburn, John; Amundsen, David S.; Acreman, David M.; Smith, Chris; Browning, Matthew K.; Manners, James; Wood, Nigel	Results from a set of three-dimensional numerical experiments of a hot Jupiter atmosphere							
6	☐ 2017ApJ...841...30T	1.000	05/2017	A	E F	X	R C	S	U
	Tremblin, P.; Chabrier, G.; Mayne, N. J.; Amundsen, D. S.; Baraffe, I.; Debras, F.; Drummond, B.; Manners, J.; Fromang, S.	Advection of Potential Temperature in the Atmosphere of Irradiated Exoplanets: A Robust Mechanism to Explain Radius Inflation							
7	☐ 2017A&A...601A.120B	1.000	05/2017	A	E F	X	R C	S	U
	Boutle, Ian A.; Mayne, Nathan J.; Drummond, Benjamin; Manners, James; Goyal, Jayesh; Hugo Lambert, F.; Acreman, David M.; Earnshaw, Paul D.	Exploring the climate of Proxima B with the Met Office Unified Model							
8	☐ 2017A&A...598A..97A	1.000	02/2017	A	E F	X	R C	S	U
	Amundsen, David S.; Tremblin, Pascal; Manners, James; Baraffe, Isabelle; Mayne, Nathan J.	Treatment of overlapping gaseous absorption with the correlated-k method in hot Jupiter and brown dwarf atmosphere models							
9	☐ 2016A&A...595A..36A	1.000	10/2016	A	E F	X	R C	S	U
	Amundsen, David S.; Mayne, Nathan J.; Baraffe, Isabelle; Manners, James; Tremblin, Pascal; Drummond, Benjamin; Smith, Chris; Acreman, David M.; Homeier, Derek	The UK Met Office global circulation model with a sophisticated radiation scheme applied to the hot Jupiter HD 209458b							
10	☐ 2014A&A...564A..59A	1.000	04/2014	A	E F	X	R C	S	U
	Amundsen, David S.; Baraffe, Isabelle; Tremblin, Pascal; Manners, James; Hayek, Wolfgang; Mayne, Nathan J.; Acreman, David M.	Accuracy tests of radiation schemes used in hot Jupiter global circulation models							



k-term

Figure 5: Scaling behviour of three k-terms for CO2 in band 4 of the HadGEM spectral file. The *x* axis is the pressure/temperature combination which is logaritmically spaced in pressure starting from 1Pa on the left to 1000 hPa on the right. Three temperatures are used for each pressure: 190, 240, 290K.