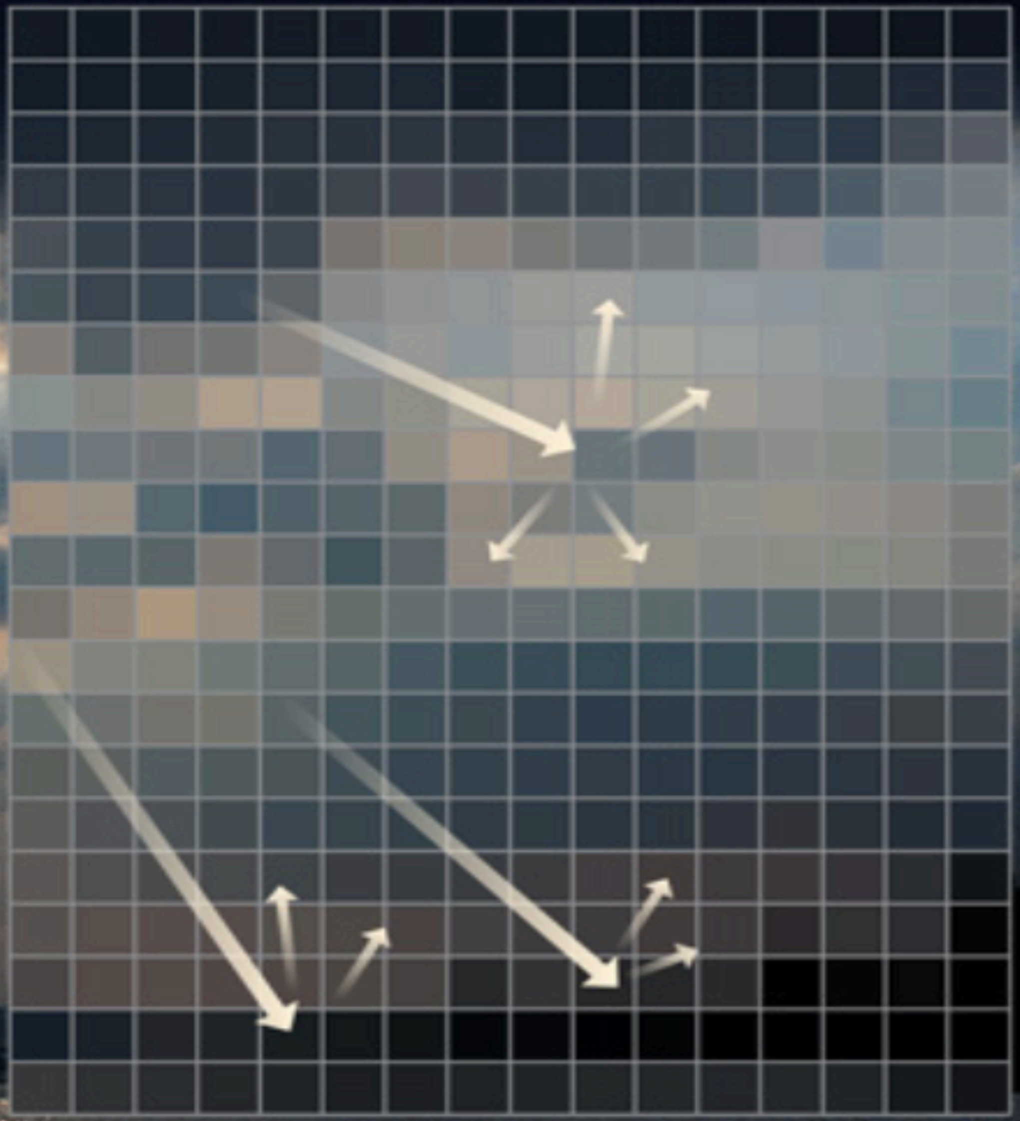
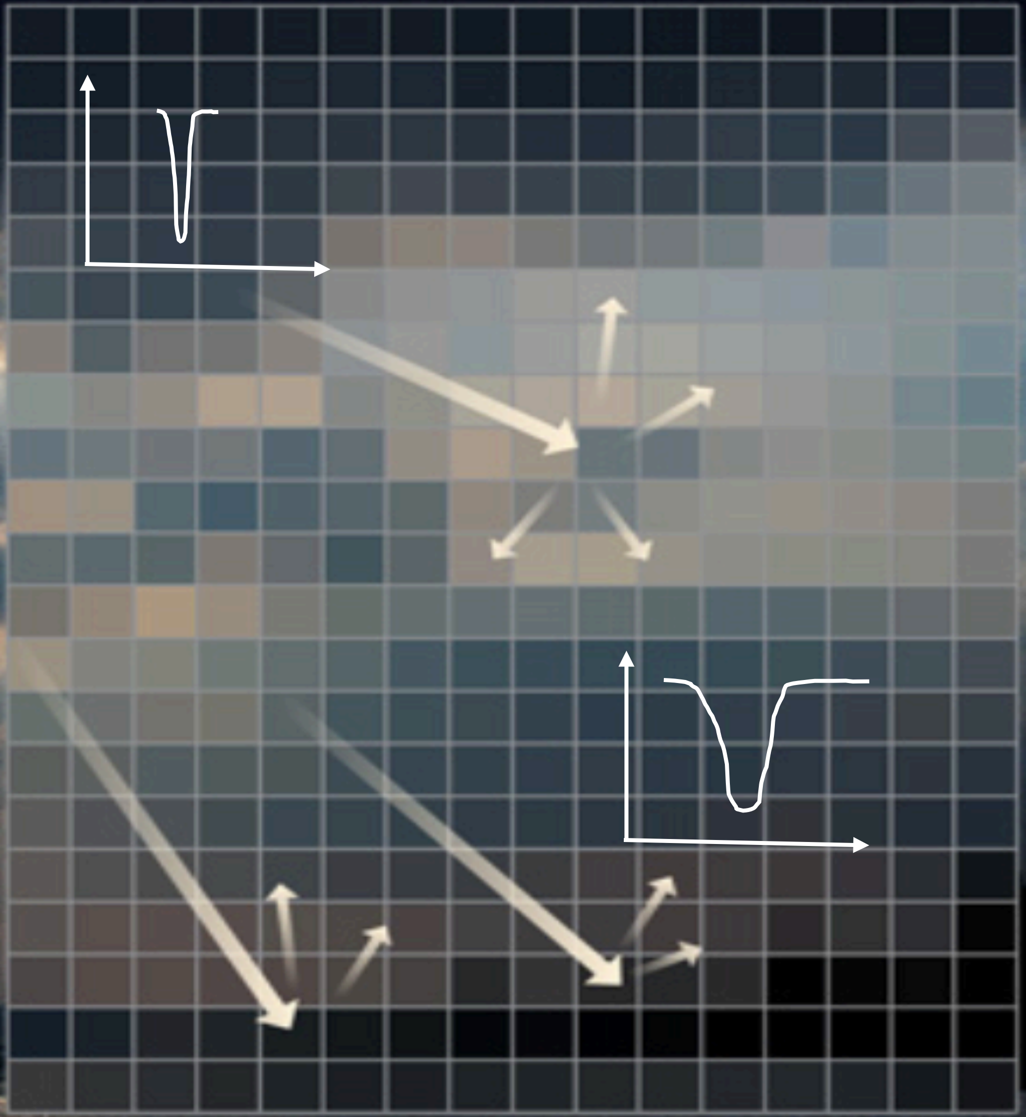
Radiation in the next generation of weather forecast models



ECMWF | Reading | 21 - 24 May 2018

Line-by-line absorption of atmospheric gases and uncorrelated k-distribution models



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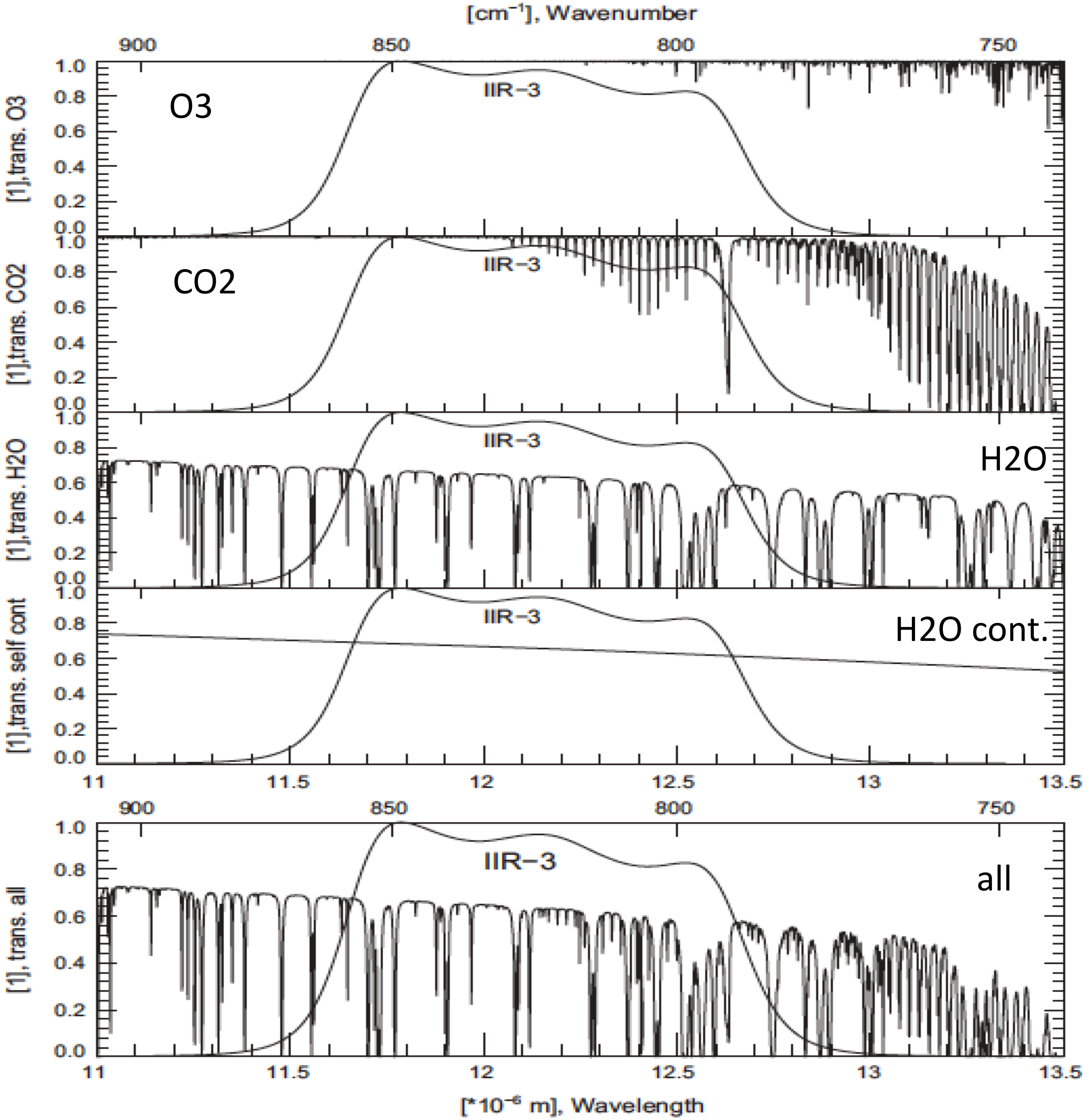
Florian Tornow, Rene Preusker
Free University Berlin

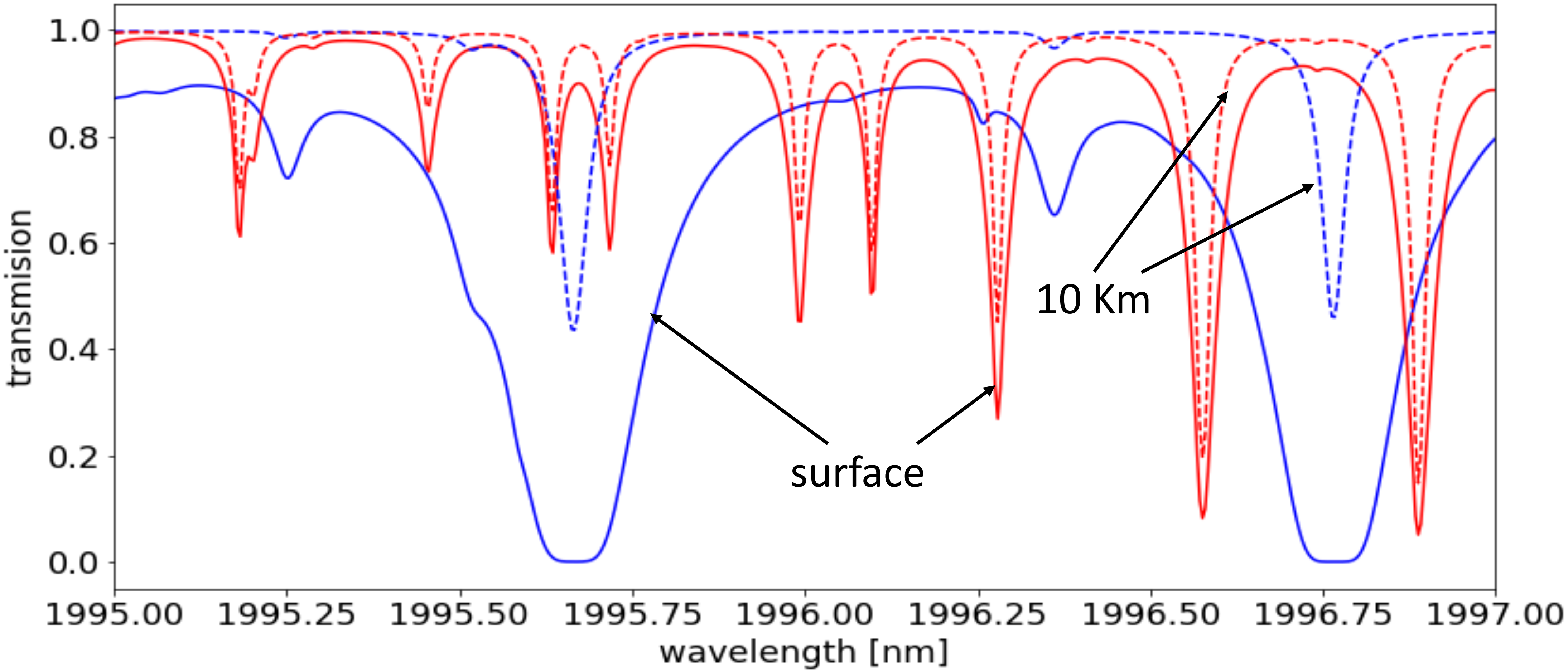


Problem understanding - Atmospheric transmission

Atmospheric transmission in the spectral subinterval of the CALIPSO-IIR, channel 3 for a mid-latitude summer standard atmosphere: all gases (bottom) and specific transmissions of different species (top); separated from bottom to top for: water vapor self-continuum only, water vapor (local lines + self-continuum + foreign continuum), carbon dioxide and ozone; response function of Channel 3 of CALIPSO-IIR; spectroscopic databases are HITRAN-2008 and the MT-CKD 2.4 water-vapour continuum

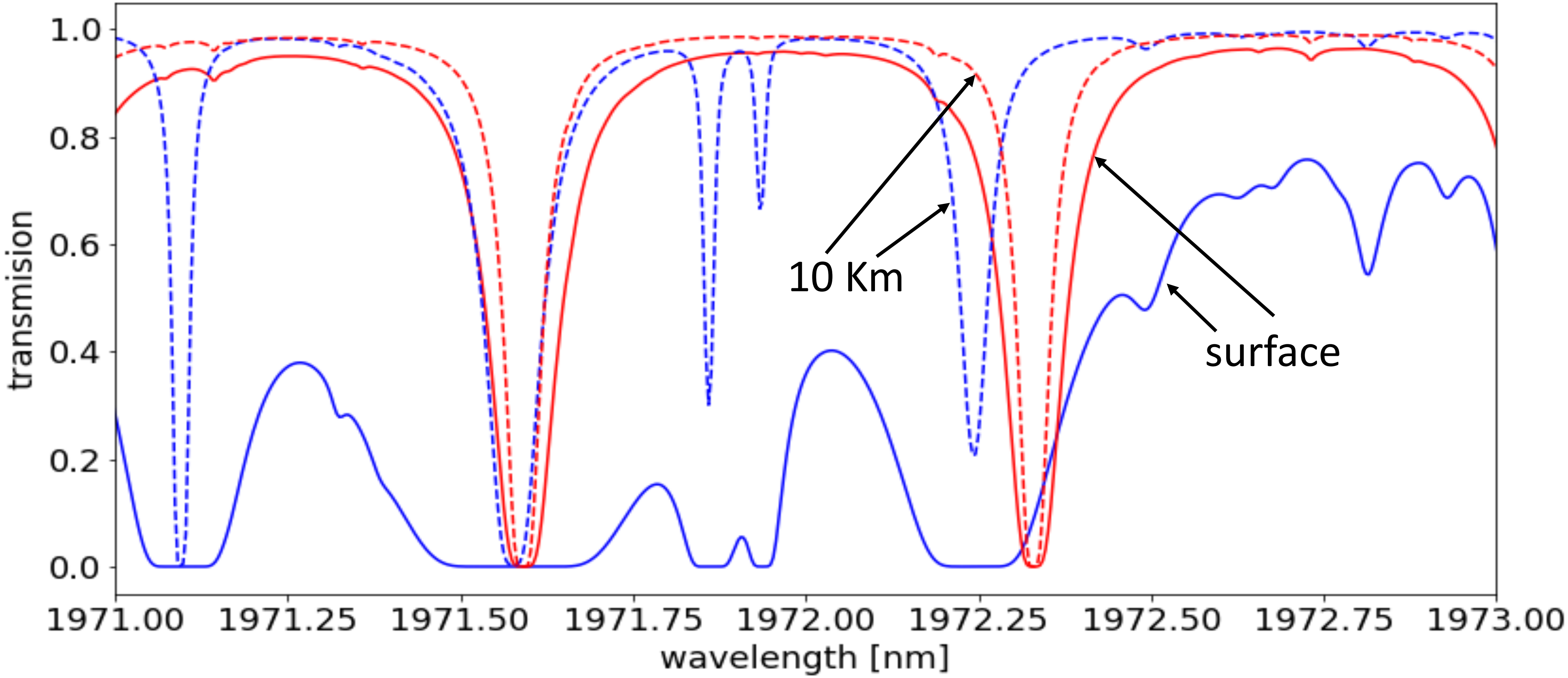
[Doppler et al., 2014]

Spectral transmission: H2O and CO2



Transmission of H20 (blue lines) and CO2 (red lines) from TOA to surface (full line) and from TOA to 10 km; Mid-latitude summer Atmosphere.

Spectral transmission: H2O and CO2



Transmission of H20 (blue lines) and CO2 (red lines) from TOA to surface (full line) and from TOA to 10 km; Mid-latitude summer Atmosphere.

K-bin Background

Most solutions of radiative transfer are based on Beers Law

$$I_\nu(s) = I_\nu(0)\exp[-k_\nu \cdot s]$$

$$Trans_\nu(s) = \exp[-k_\nu \cdot s]$$

But „real world“ instruments (like MODIS) are not monochromatic

$$Trans(\nu, \Delta\nu, s) = \frac{1}{\Delta\nu}\int \exp[-k_\nu(p_0, T_0)\cdot s]d\nu$$

and the „real world“ atmosphere is not homogeneous in the vertical

$$Trans(\nu, \Delta\nu, s) = \frac{1}{\Delta\nu}\int \exp\left[-\sum_{1}^{\text{layer}} k_\nu(p_l, T_l)]\cdot s_l\right]d\nu$$

K-bin - Solution 1: Line-by-Line calculation

$$Trans(\nu,\Delta\nu,s)=\frac{1}{\Delta\nu}\int\exp\left[-\sum_{1}^{\text{layer}}k_{\nu}(p_l,T_l)]\cdot s_l\right]d\nu$$

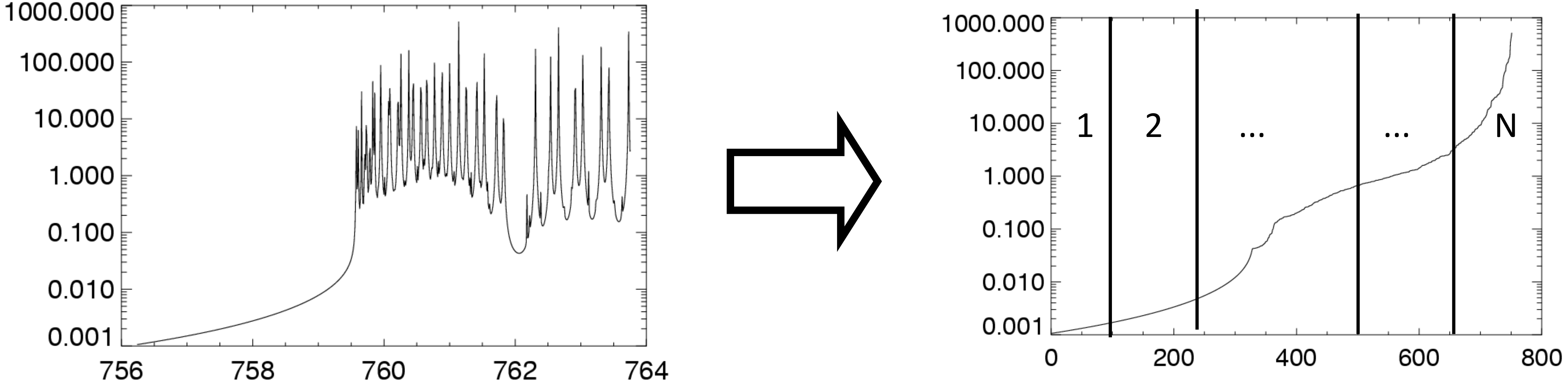
⇩

$$Trans(\nu,\Delta\nu,s)\approx\frac{1}{\Delta\nu}\sum_{i}^{iiiii}\delta\nu\cdot\exp\left[-\sum_{l}^{\text{layer}}\bar{k}_i(p_l,T_l)\cdot s_l]\right]$$

Since *iiiii* is usually big (e.g. several thousands for the MERIS O2 A-band channel), Line-by-Line calculations are computationally expensive if scattering is included.
However they are precise !

K-bin - Solution 2: correlated k-distribution

$$Trans(\nu,\Delta\nu,s)\approx\frac{1}{\sum w_i}\sum_i^N w_i\cdot\exp\left[-\sum_l^{\text{layer}}\bar{k}_i(p_l,T_l)\cdot s_l]\right]$$



1. Separate the spectral interval into many small “monochromatically valid” sub-intervals.
2. Sort the extinction coefficients
3. Group of the extinction coefficients into *N* classes of similar k´s (Find the **mapping function**)
4. Make radiative transfer calculations only for the *N* classes instead for *iiii* sub-intervals

K-bin - Solution 2: correlated k-distribution

$$Trans(\nu, \Delta\nu, s) \approx \frac{1}{\sum w_i} \sum_{i}^{N} w_i \cdot \exp\left[-\sum_{l}^{\text{layer}} \bar{k}_i(p_l, T_l) \cdot s_l] \right]$$

The sorting and grouping of the k´s is made in **each** layer. The above equation can only work, if the wavelengths belonging to each class are (almost) the same. (If the mapping functions of the layers are **correlated**). But the assumed correlation is not always fulfilled e.g. MODIS band 5 (different species) and even in MERIS band 11 (overlapping wings).

Lacis, A. A., and V. Oinas, A description of the correlated k distribution …, J. Geophys. 1991

K-bin - Solution 3: “uncorrelated” k-distribution

The basic k-distribution equation remains (*M*: mapping function, *R*: channel response, *w*: weight of term):

$$Trans(\nu, \Delta\nu, s) = \frac{1}{\sum w_i} \sum_i^N w_i \cdot \exp\left[-\sum_l^{\text{layer}} \bar{k}_i(p_l, T_l) \cdot s_l] \right]$$

$$w_i = \int_{\Delta\nu} R(M_i) d\nu \qquad \bar{k}_i = \langle k(M_i) \rangle$$

But the methods for finding the **optimal** mapping function (*M*) are new.

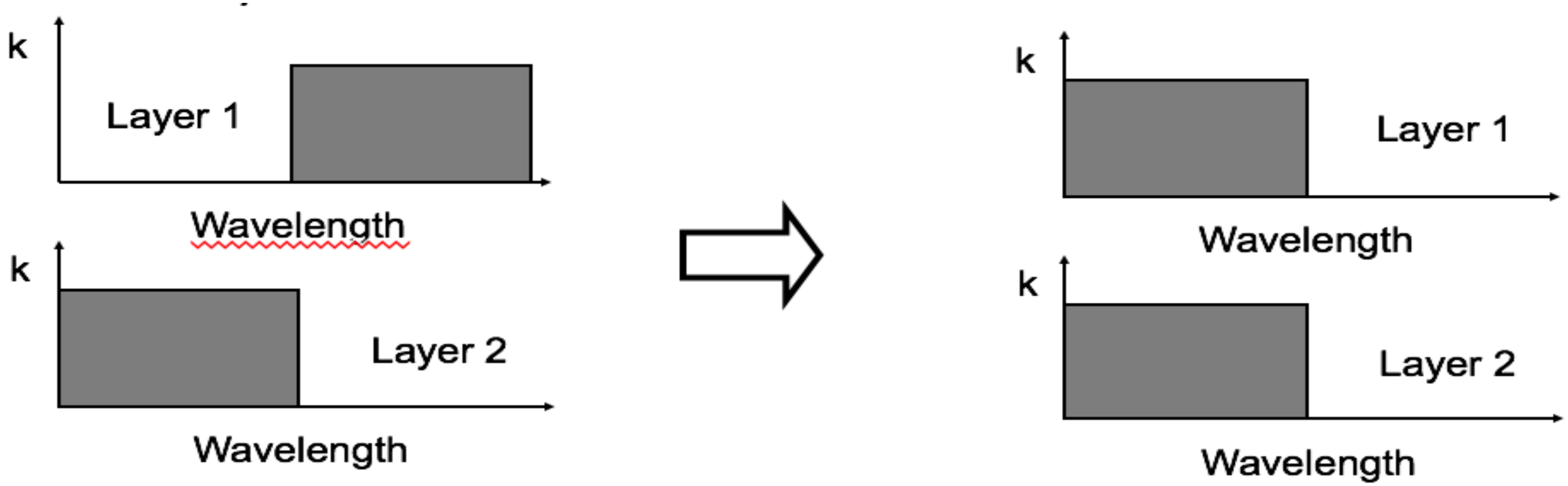
What is “uncorrelated”?

K-bin - Solution 3: “uncorrelated” k-distribution

- The mapping function must allow the precise approximation of the total transmission!

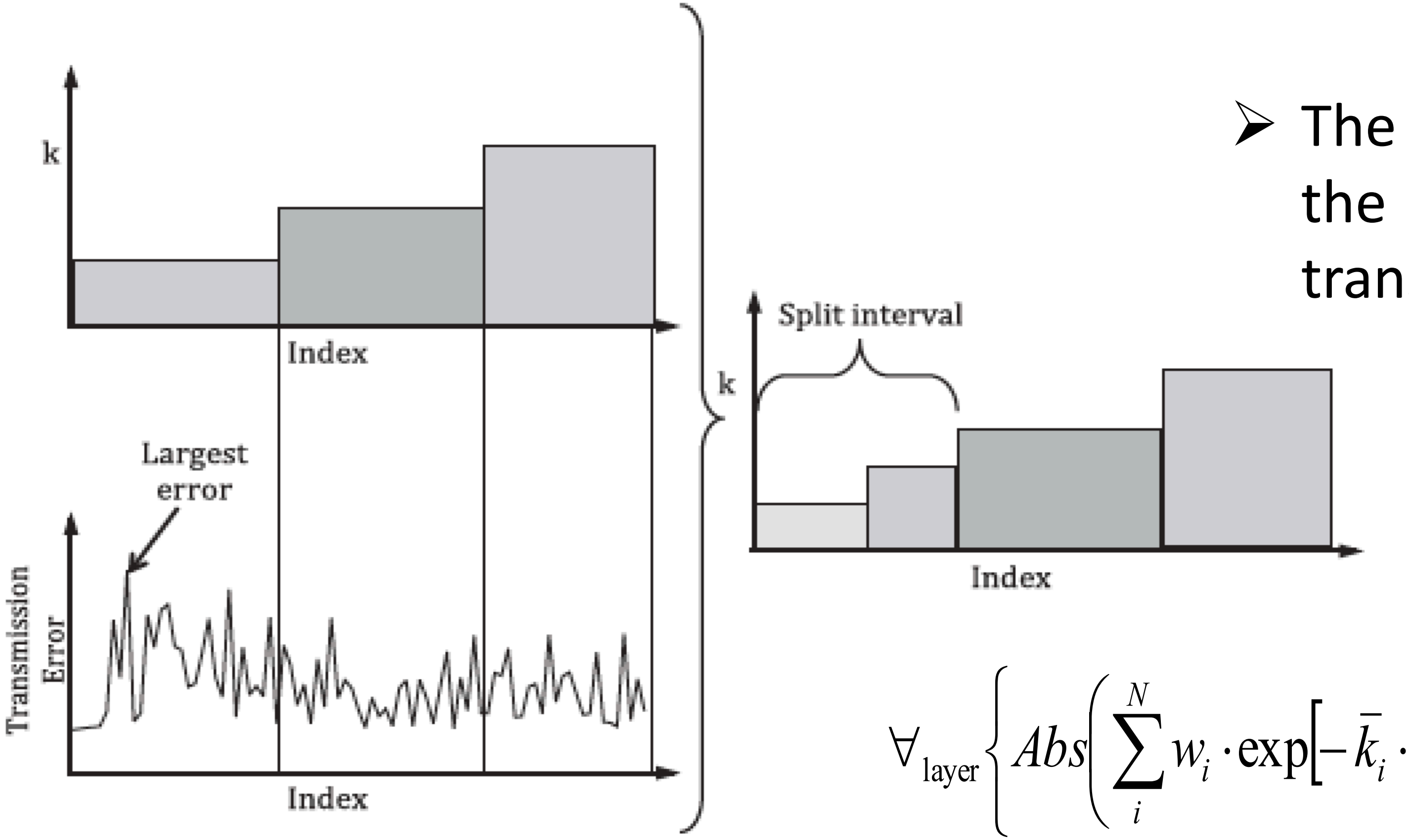
$$Abs\left(\frac{1}{\sum w_i}\sum_{i}^{N} w_i\cdot\exp\left[-\sum_{l}^{\text{layer}}\bar{k}_i(p_l,T_l)\cdot s_l]\right]-\int R(\nu)\cdot\exp\left[-\sum_{1}^{\text{layer}}k_\nu(p_l,T_l)]\cdot s_l\right]d\nu\right)\longrightarrow 0$$

- The mapping function must be the same for each layer (= 100% correlation)!



In this (extreme) example the correlated k-distribution would sort the coefficients (wrongly assuming spectral correlation of the extinction coefficients) and calculate a total transmission of 0.5 (grey means transmission of 0 and white of 1) whereas the real transmission is 0!

K-bin - Solution 3: “uncorrelated” k-distribution



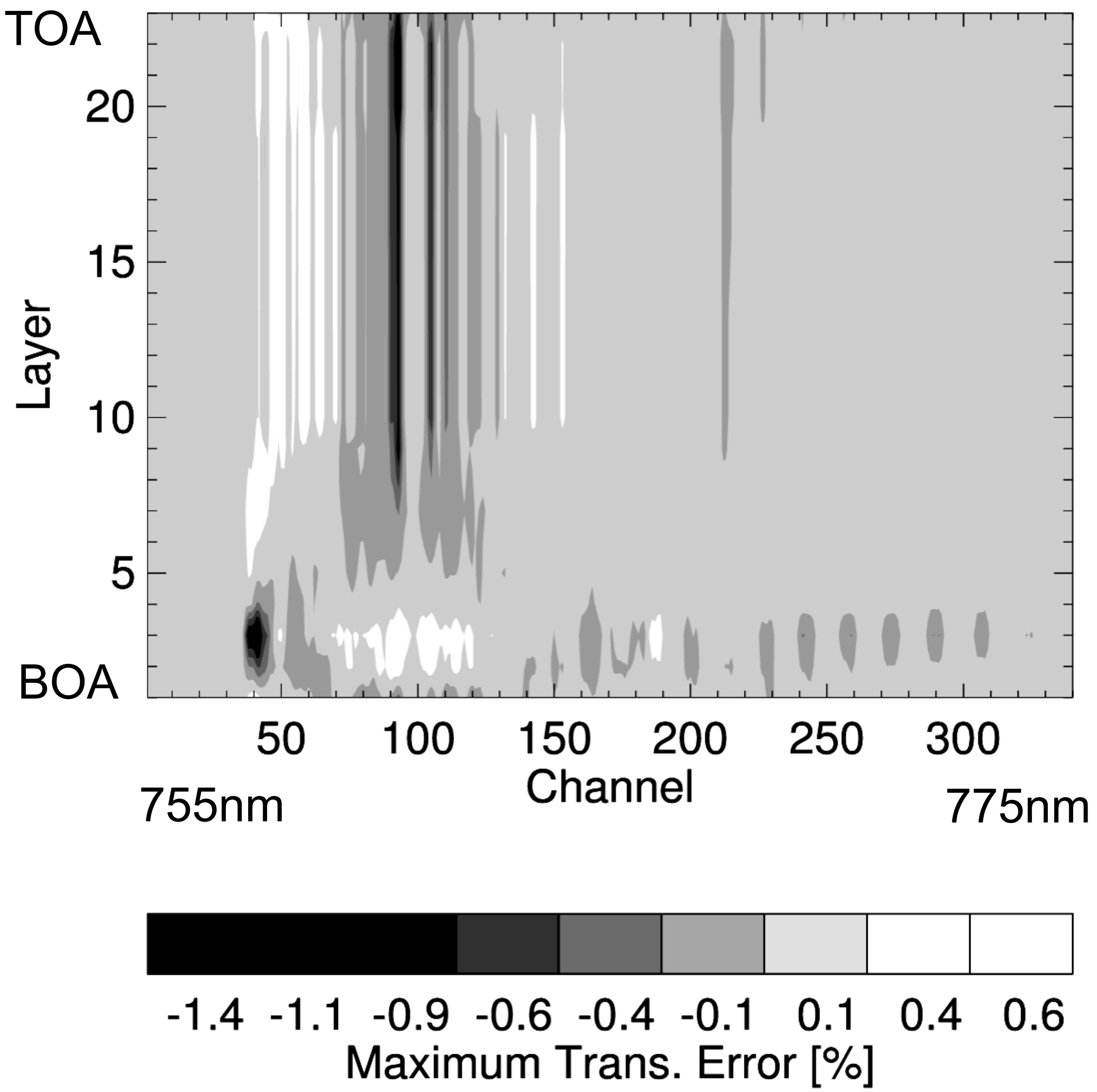
- The mapping function must allow the precise approximation of the transmission in each layer!

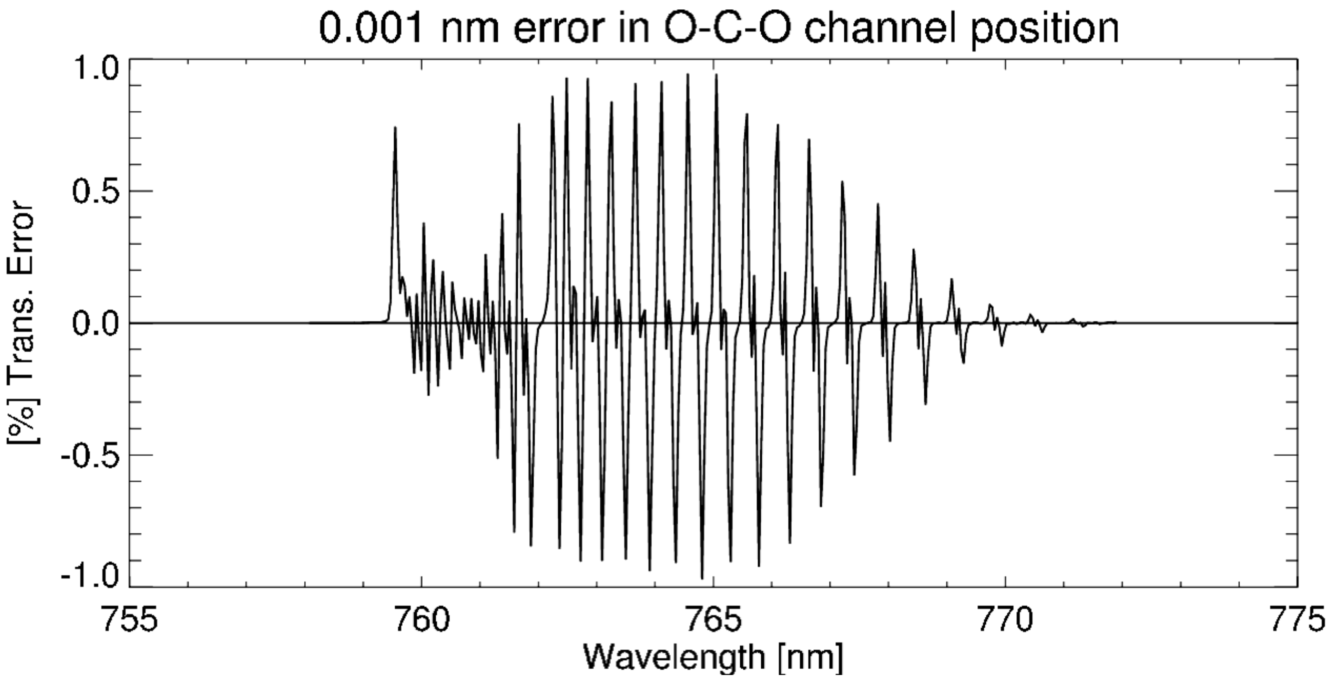
$$\forall_{\text{layer}} \left\{ Abs\left(\sum_{i}^{N} w_i \cdot \exp\left[-\bar{k}_i \cdot s_l\right] - \int \exp\left[-k_\nu \cdot s_l\right] d\nu \right)_l \longrightarrow 0 \right.$$

Schematic representation of the k-bin approach; the broadband wavenumber interval is initially subdivided into N k-bin intervals; the interval with the highest error in transmission compared to monochromatic transmittances is subdivided into two intervals; the process is then iteratively repeated until all transmittance errors fall below a user-defined threshold (see Doppler et al., 2014).

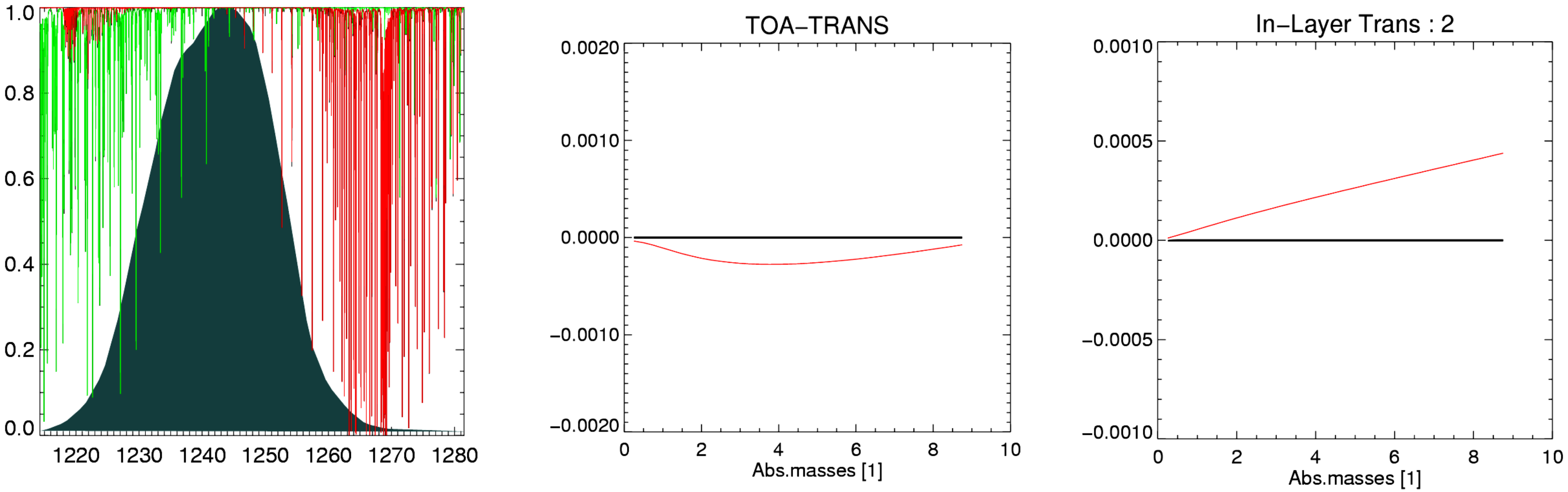
K-bin - Solution 3: Results for OCO

The maximum simulated transmission error for O-C-O’s oxygen channels (fwhm ~0.08nm) is below 1.4%, the mean transmission **error is below 0.15%** if O-C-O’s channels are simulated with **300 k-terms**. This is the same order of magnitude as for a (small !) 0.001nm error in O-C-O’s channel position.



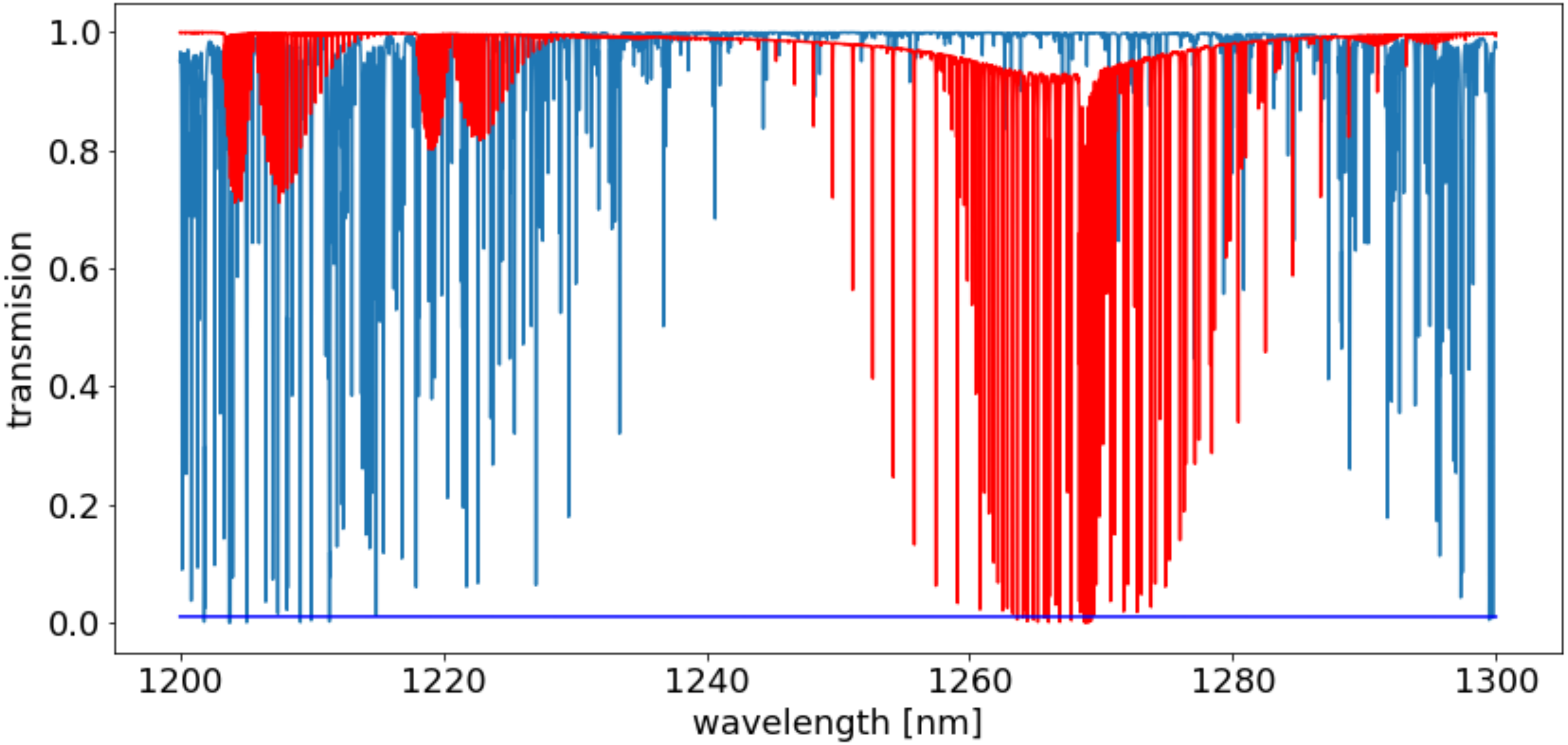


K-bin - Solution 3: Results for MODIS 1.24 µm channel



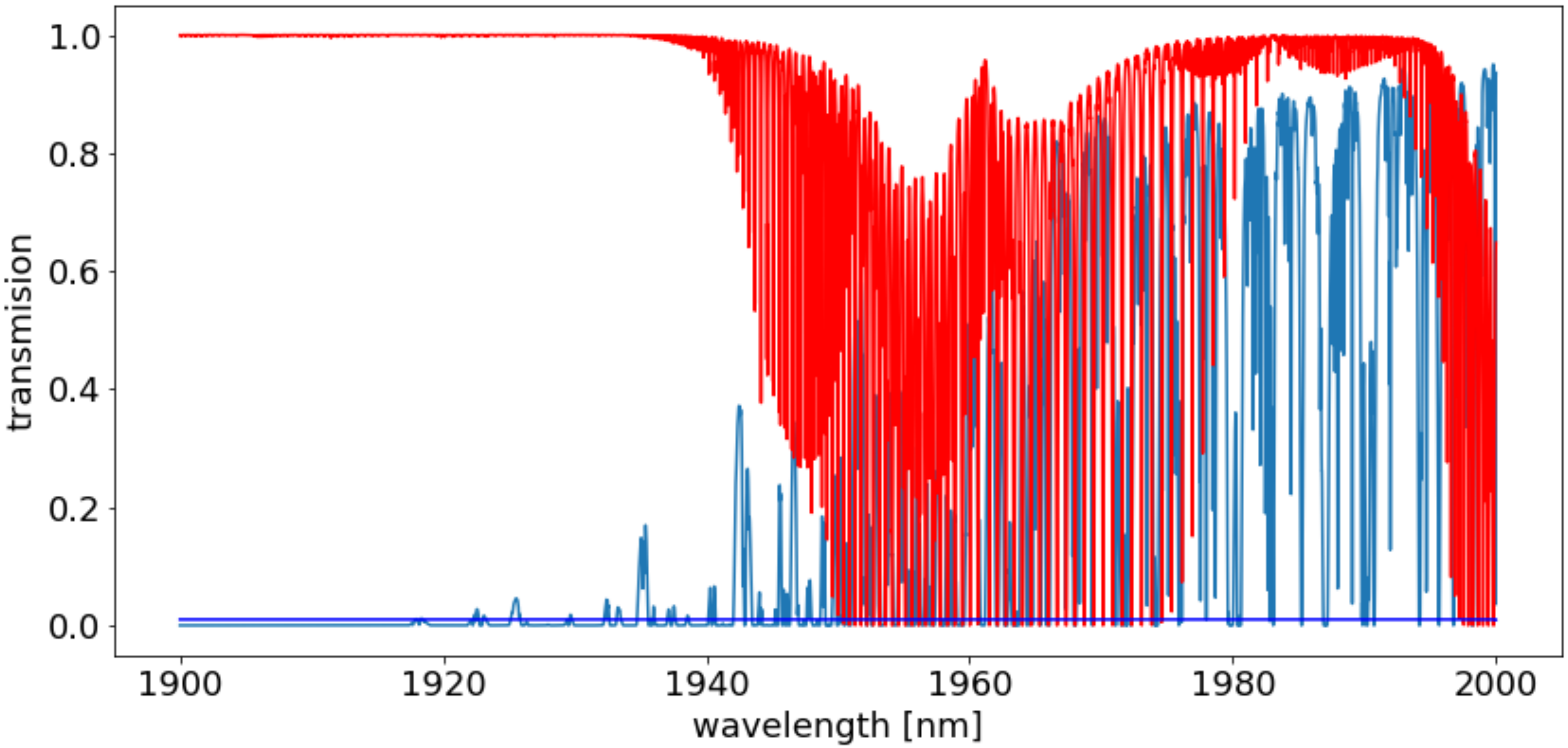
MODIS Band 5 is influenced by H2O and O2. The main amount of the total absorption is in the lower atmosphere, which is determined by water vapor. In the case of a high cloud the correlated K-distribution would produce wrong results, since then the transmission is determined by oxygen absorption, which's spectral features are **not correlated** with the spectral features of water vapor. The new method produced results, that are better than 0.1% (abs.) in each layer and in total when using **40 terms**.

K-bin - Solution 3: Results for 1.2 – 1.3µm broadband



This band is influenced by H2O, O2, NO2; The main amount of the total absorption is in the lower atmosphere, which is determined by water vapor.

K-bin - Solution 3: Results for 1.9 – 2.0µm broadband



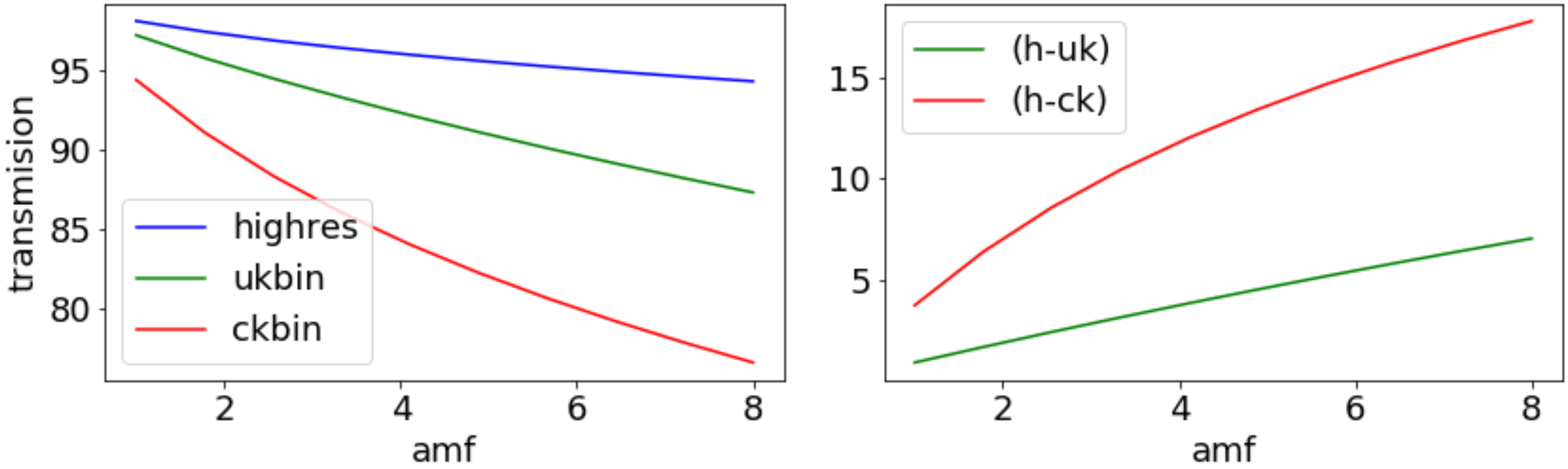
This band is influenced by H2O, CO2; The main amount of the total absorption is in the lower atmosphere, which is determined by water vapor.

K-bin - Solution 3: Atmospheric Layers

50 km				9.5 hPa	275.7 K
	Layer 1	224.4 K	0.17 %		
20 km				59.5 hPa	219.2 K
	Layer 2	215.8 K	4.52 %		
10 km				281.0 hPa	235.3 K
	Layer 3	253.7 K	30.50 %		
5km				554.0 hPa	267.2 K
	Layer 4	276.9 K	43.68 %		
2 km				802.0 hPa	285.2 K
	Layer 5	287.5 K	61.41 %		
1 km				902.0 hPa	289.7 K
	Layer 6	291.7 K	71.45 %		
0.1 km				1001.9 hPa	293.7 K
	Layer 7	293.7 K	71.99 %		
surface				1013.0 hPa	294.2 K

K-bin - 50 terms: Results for 1.9 – 2.0μm broadband

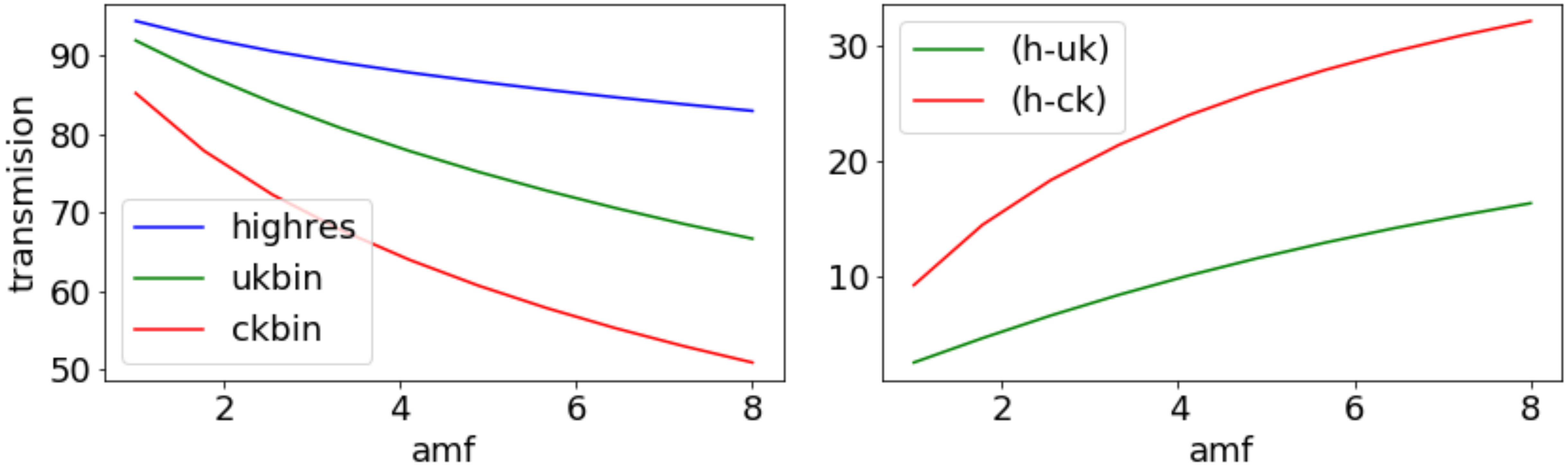
TOA to Layer 4: 20 - 50 km



Transmission to layer versus air-mass (amf) estimated by line-bay-line (blue), correlated (red) and un-correlated k-binning (green); mid-latitude summer atmosphere.

K-bin - 50 terms: Results for 1.9 – 2.0μm broadband

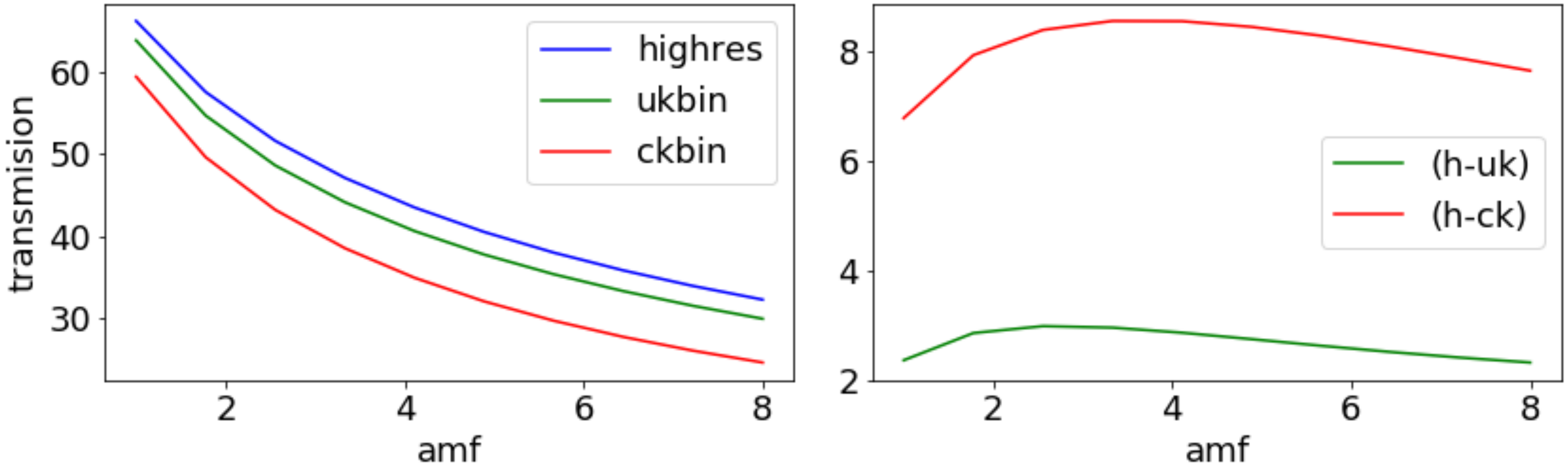
TOA to Layer 4: 10 - 20 km



Transmission to layer versus air-mass (amf) estimated by line-bay-line (blue), correlated (red) and un-correlated k-binning (green); mid-latitude summer atmosphere.

K-bin – 50 terms: Results for 1.9 – 2.0µm broadband

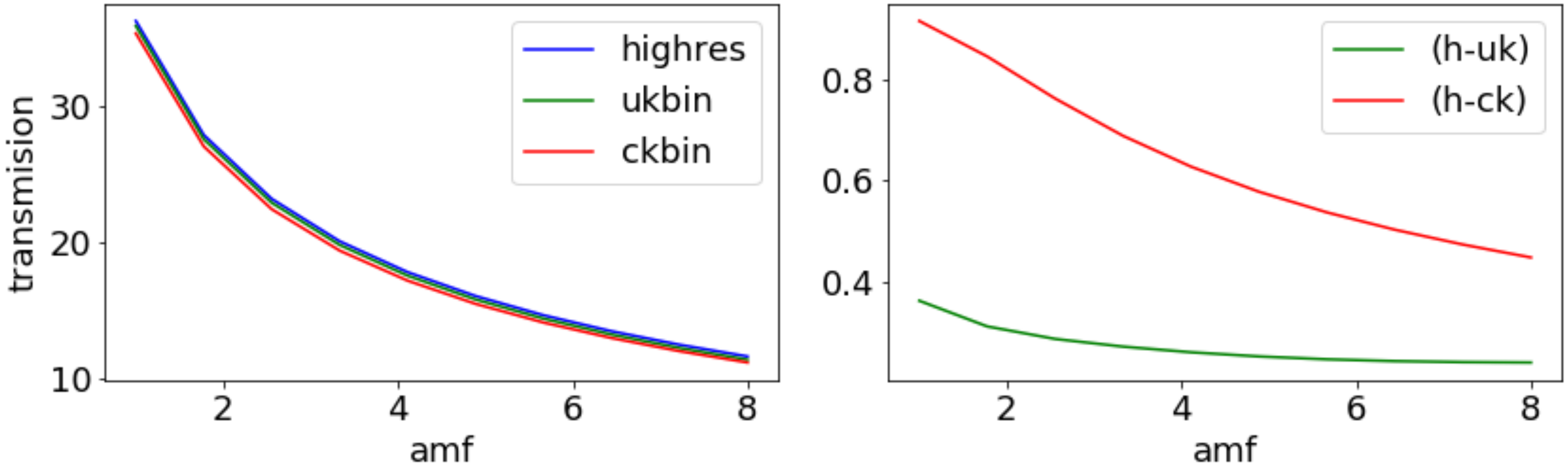
TOA to Layer 4: 5 - 10 km



Transmission to layer versus air-mass (amf) estimated by line-bay-line (blue), correlated (red) and un-correlated k-binning (green); mid-latitude summer atmosphere.

K-bin – 50 terms: Results for 1.9 – 2.0μm broadband

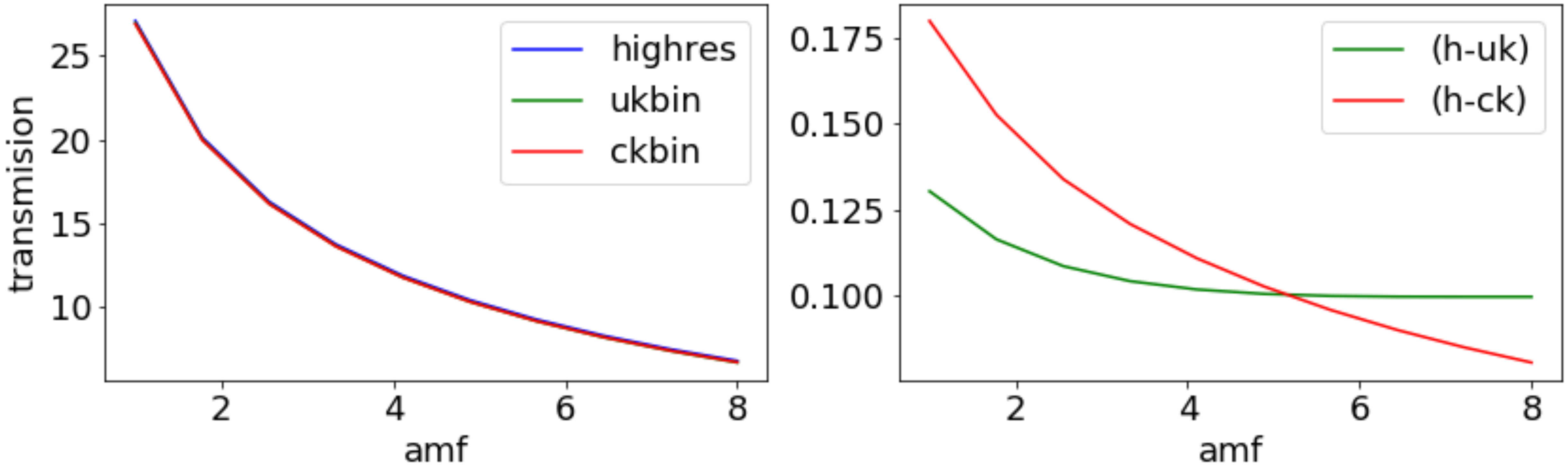
TOA to Layer 4: 2 - 5 km



Transmission to layer versus air-mass (amf) estimated by line-bay-line (blue), correlated (red) and un-correlated k-binning (green); mid-latitude summer atmosphere.

K-bin – 50 terms: Results for 1.9 – 2.0μm broadband

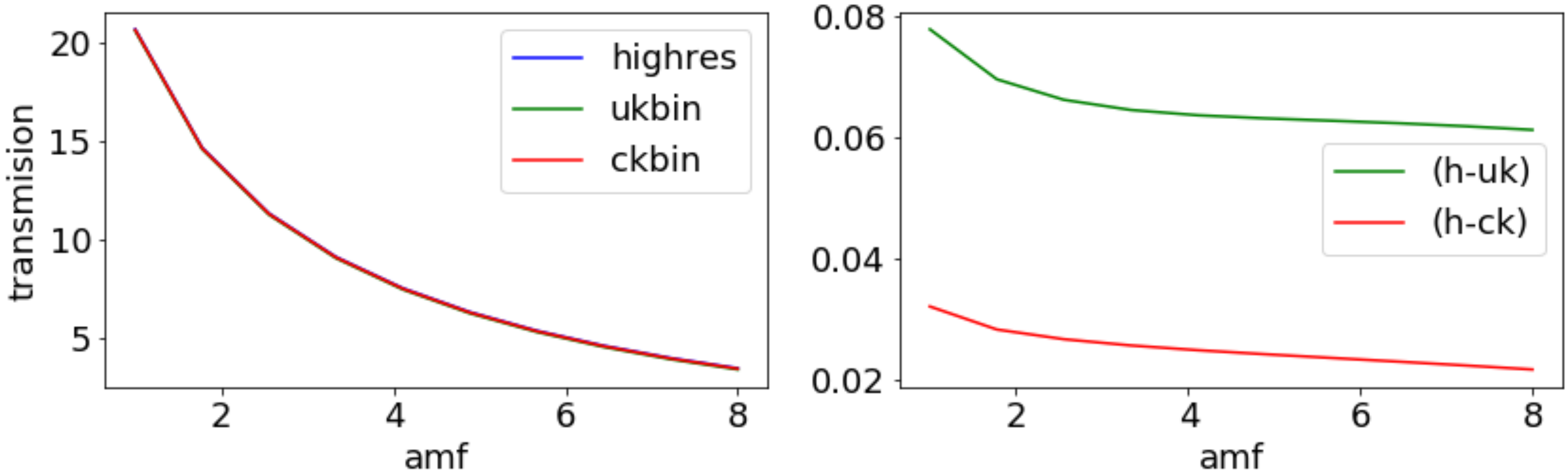
TOA to Layer 4: 1 - 2 km



Transmission to layer versus air-mass (amf) estimated by line-bay-line (blue), correlated (red) and un-correlated k-binning (green); mid-latitude summer atmosphere.

K-bin – 50 terms: Results for 1.9 – 2.0μm broadband

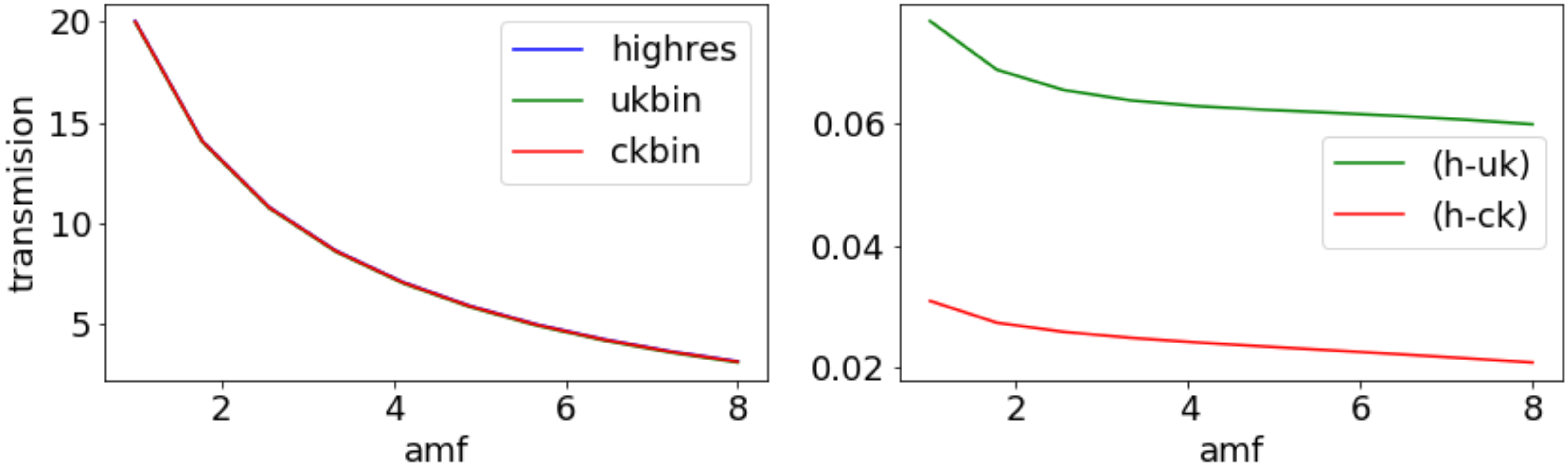
TOA to Layer 4: 0.1 - 1 km



Transmission to layer versus air-mass (amf) estimated by line-bay-line (blue), correlated (red) and un-correlated k-binning (green); mid-latitude summer atmosphere.

K-bin – 50 terms: Results for 1.9 – 2.0μm broadband

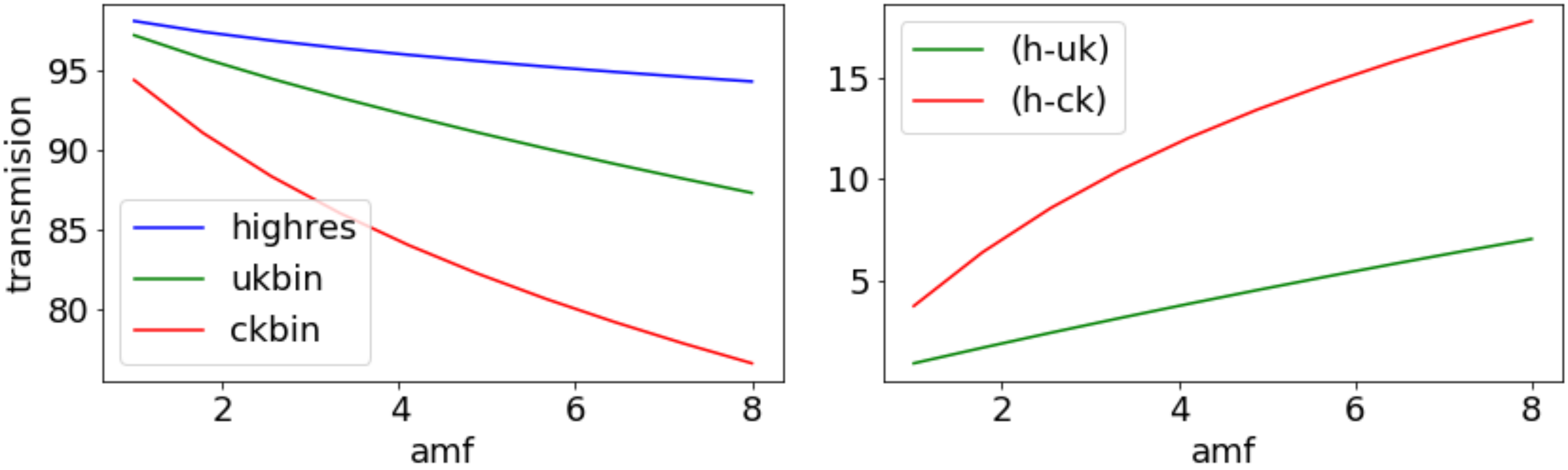
TOA to Layer 4: 0 – 0.1 km



Transmission to layer versus air-mass (amf) estimated by line-bay-line (blue), correlated (red) and un-correlated k-binning (green); mid-latitude summer atmosphere.

K-bin – 50 terms: Results for 1.9 – 2.0µm broadband

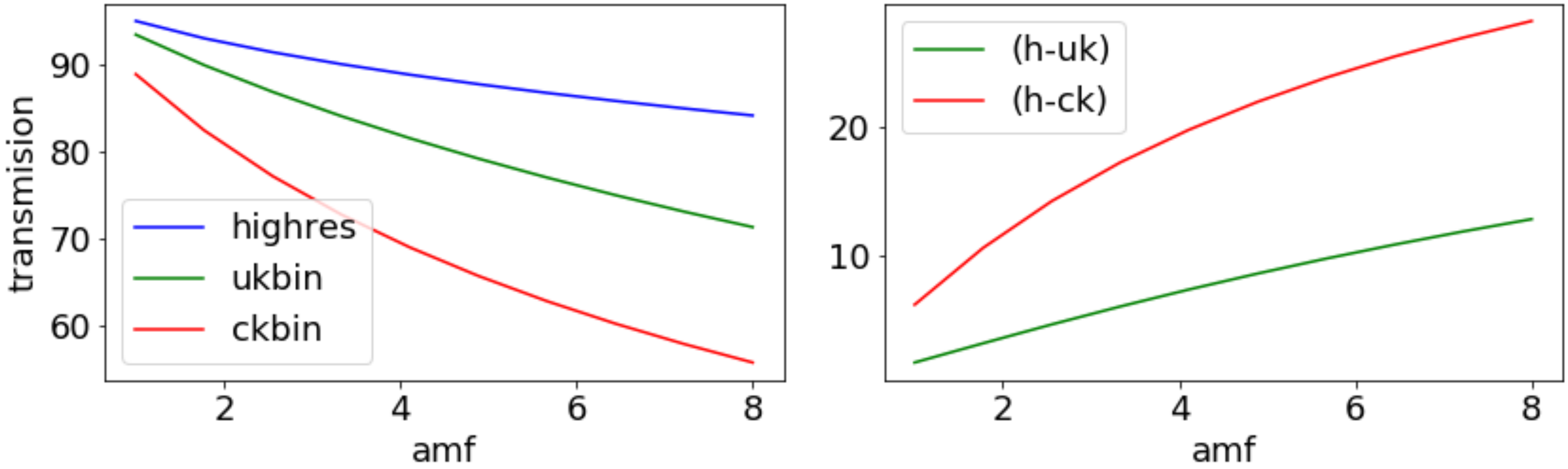
Layer 4: 20 - 50 km



Transmission of layer versus air-mass (amf) estimated by line-bay-line (blue), correlated (red) and un-correlated k-binning (green); mid-latitude summer atmosphere.

K-bin – 50 terms: Results for 1.9 – 2.0µm broadband

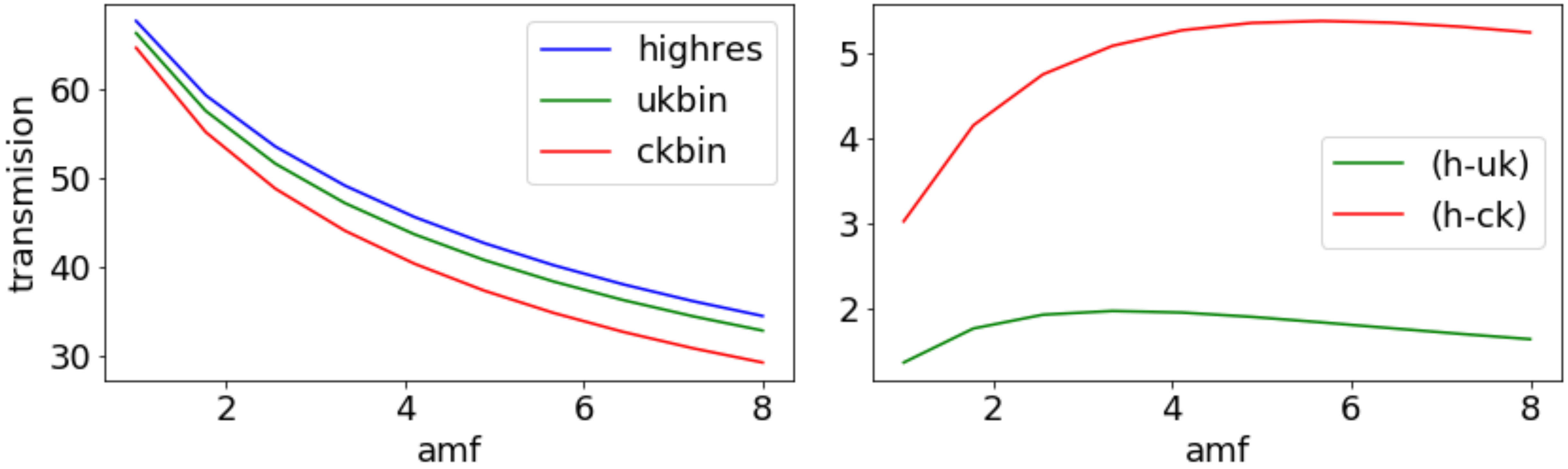
Layer 4: 10 - 20 km



Transmission of layer versus air-mass (amf) estimated by line-bay-line (blue), correlated (red) and un-correlated k-binning (green); mid-latitude summer atmosphere.

K-bin – 50 terms: Results for 1.9 – 2.0μm broadband

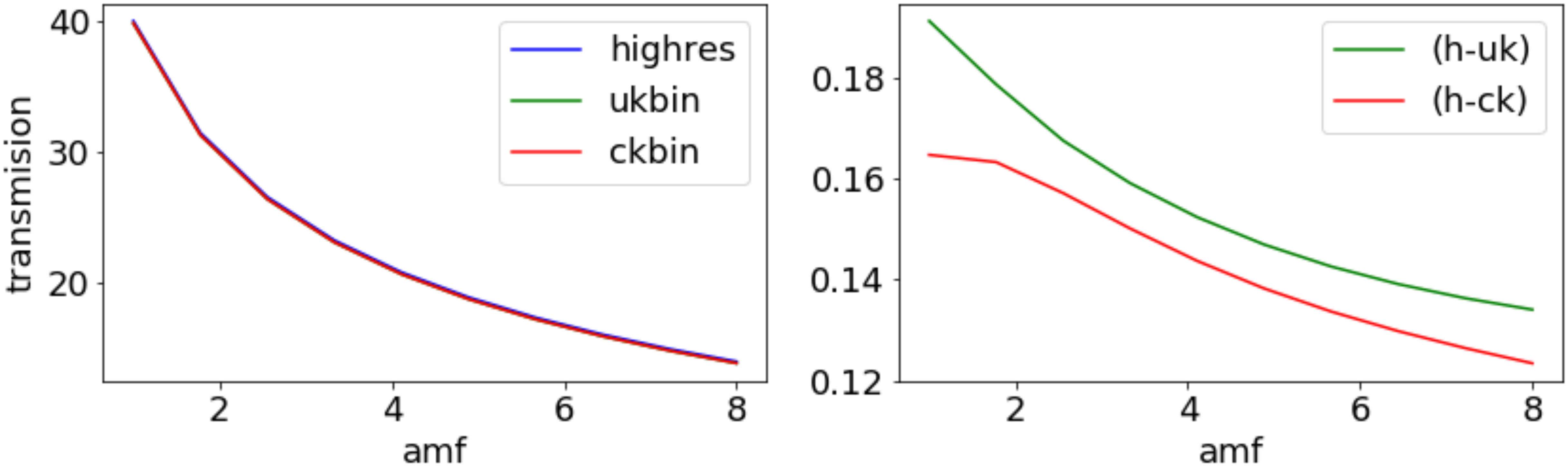
Layer 4: 5 - 10 km



Transmission of layer versus air-mass (amf) estimated by line-bay-line (blue), correlated (red) and un-correlated k-binning (green); mid-latitude summer atmosphere.

K-bin – 50 terms: Results for 1.9 – 2.0µm broadband

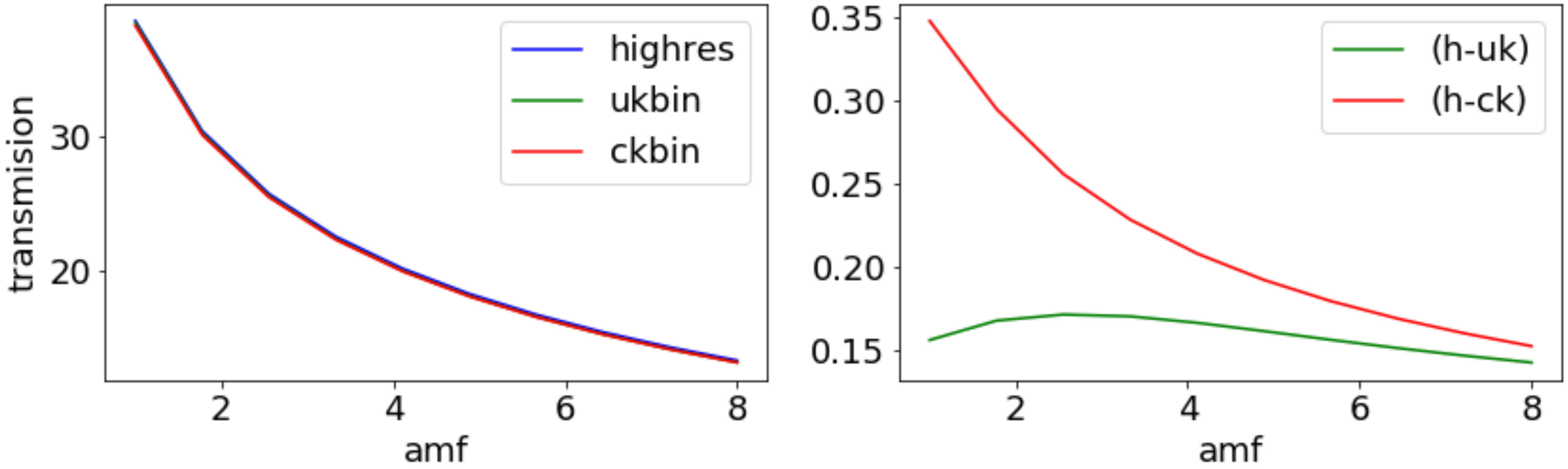
Layer 4: 2 - 5 km



Transmission of layer versus air-mass (amf) estimated by line-bay-line (blue), correlated (red) and un-correlated k-binning (green); mid-latitude summer atmosphere.

K-bin – 50 terms: Results for 1.9 – 2.0μm broadband

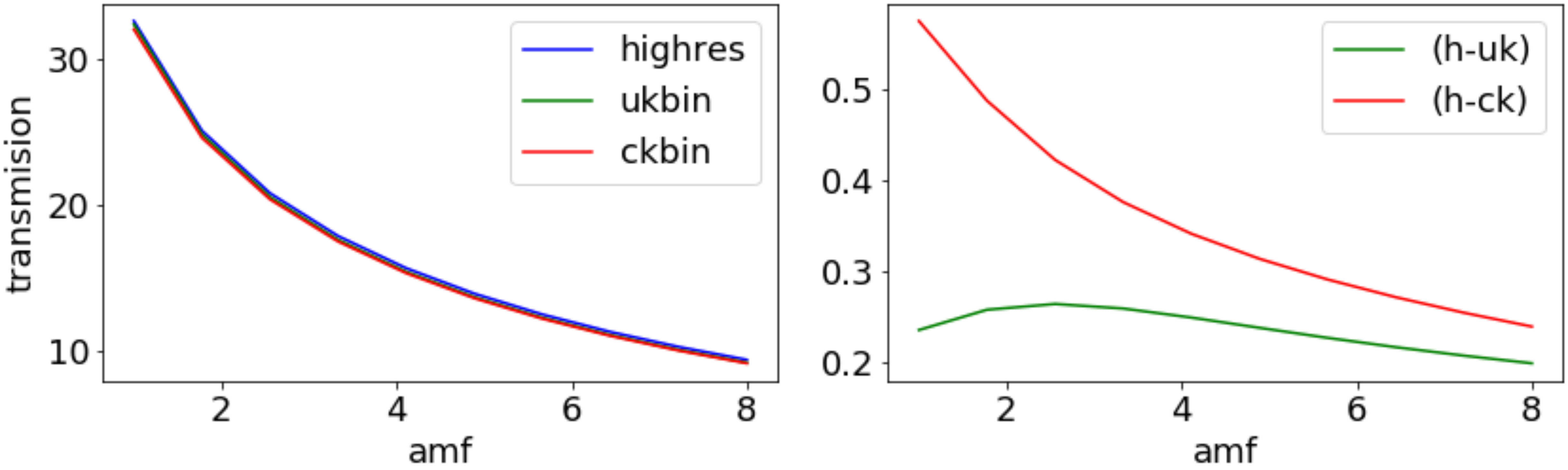
Layer 4: 1 - 2 km



Transmission of layer versus air-mass (amf) estimated by line-bay-line (blue), correlated (red) and un-correlated k-binning (green); mid-latitude summer atmosphere.

K-bin – 50 terms: Results for 1.9 – 2.0µm broadband

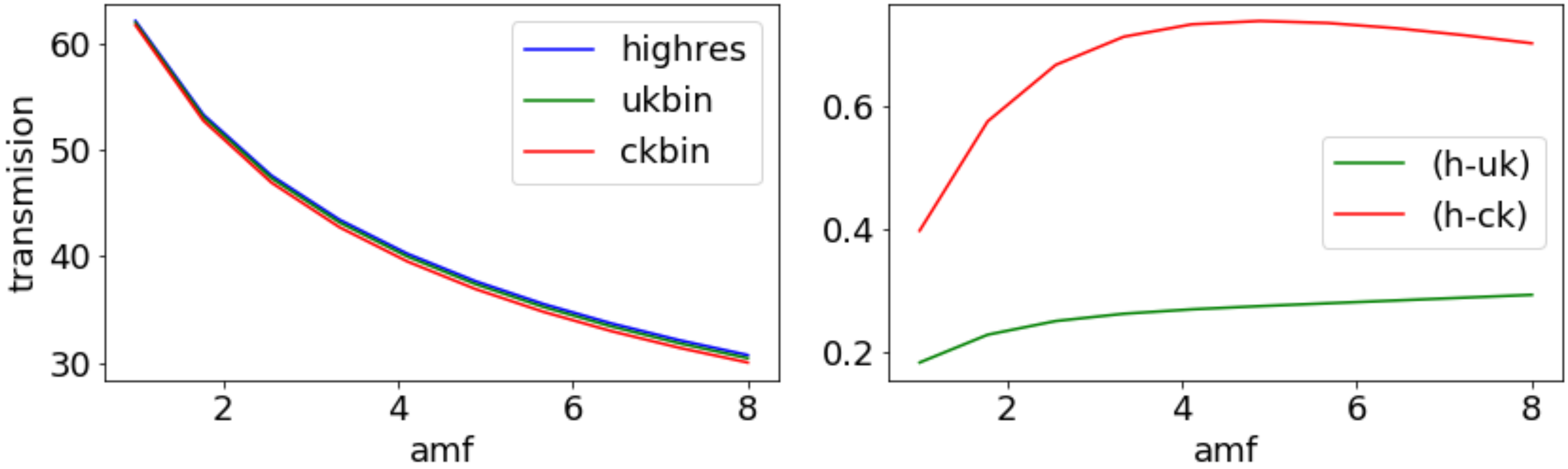
Layer 4: 0.1 - 1 km



Transmission of layer versus air-mass (amf) estimated by line-bay-line (blue), correlated (red) and un-correlated k-binning (green); mid-latitude summer atmosphere.

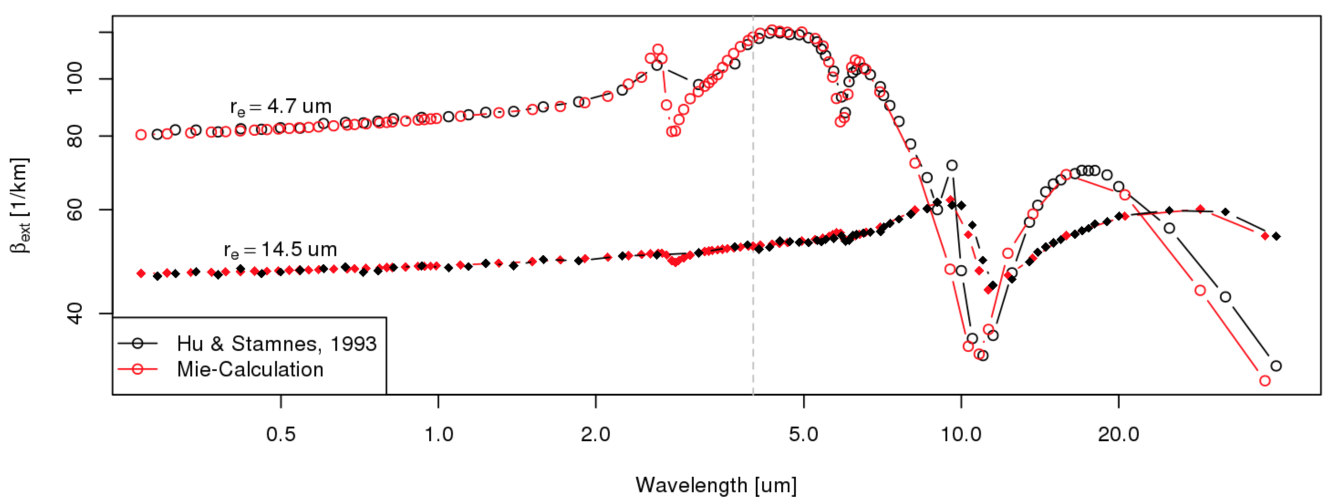
K-bin – 50 terms: Results for 1.9 – 2.0μm broadband

Layer 4: 0 – 0.1 km

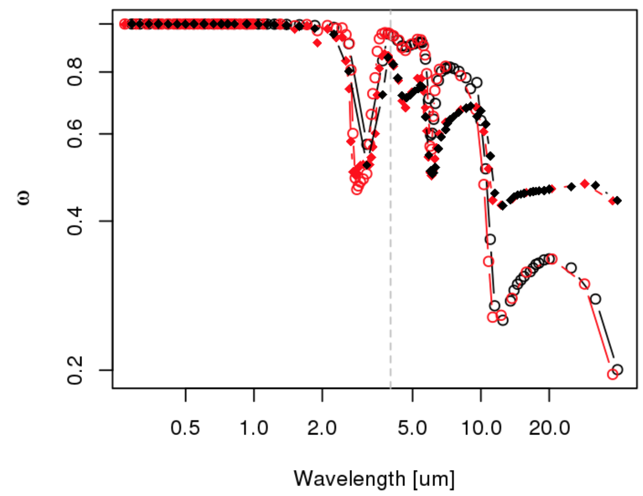


Transmission of layer versus air-mass (amf) estimated by line-bay-line (blue), correlated (red) and un-correlated k-binning (green); mid-latitude summer atmosphere.

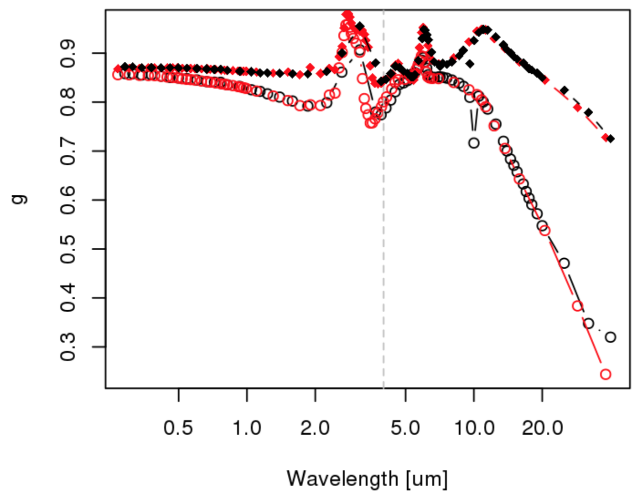
Comparison of “uncorrelated “ k-binning MOMO and RRTMG



Extinction coefficient



Single Scattering Albedo



Asymmetry Parameter g

Broadband Simulators

RRTMG (Iacono et al., 2008)

- fixed LBLRTM-based corr. k distr.
- Hu-Stamnes cloud parametrization
- SW: 0.2-12.5um; LW: 3.0-1000.0um
- 14 solar & 16 longwave bands

MOMO (Hollstein and Fischer, 2012)

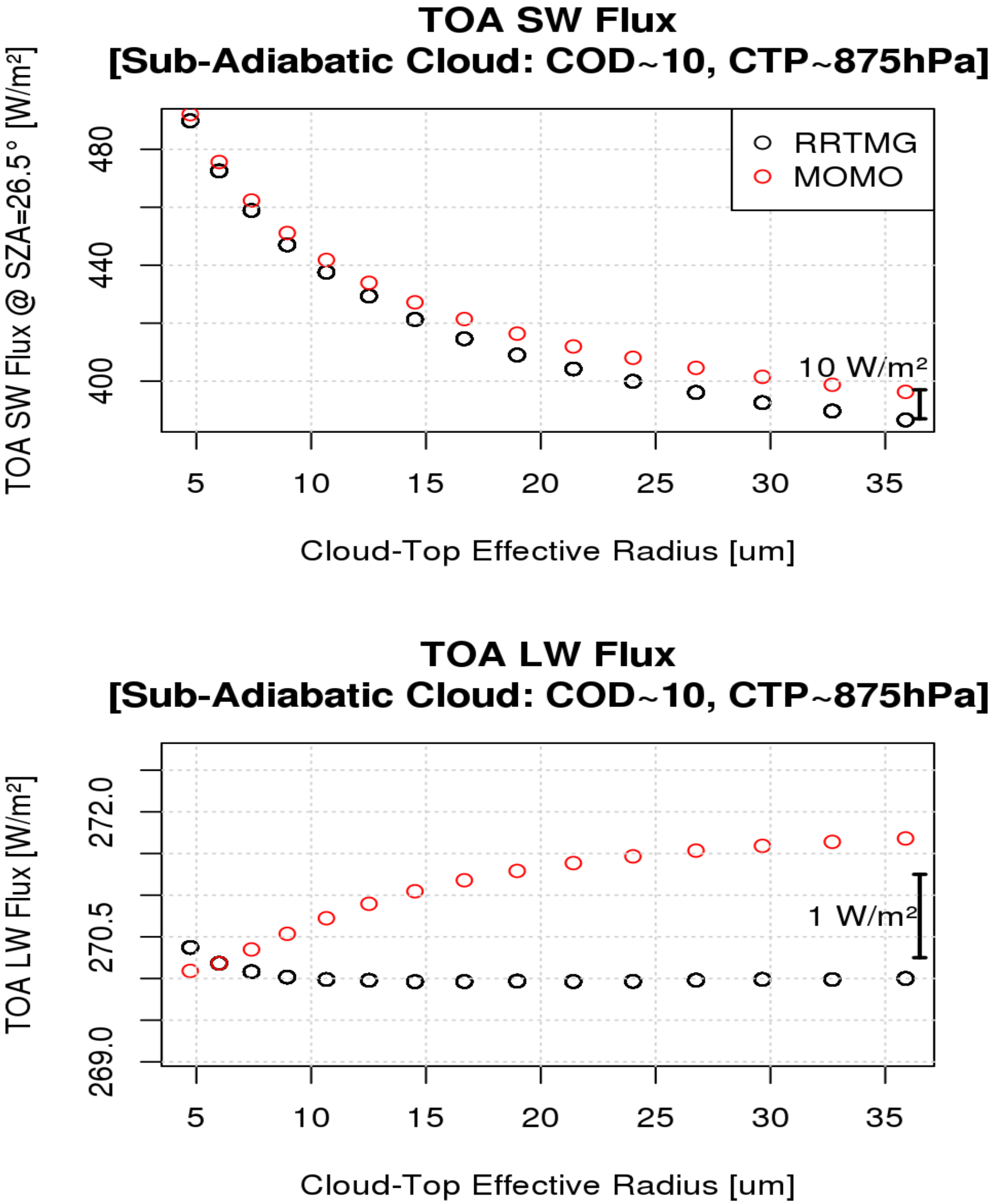
- un-correlated k-distr. (Doppler et al., 2014)
- Mie-calculated cloud and aerosol properties
- SW: 0.2-4.0um; LW: 3.0-100.0um
- 53 solar & 42 longwave spectral band
- 35 quadrature points

Both RTMs are plane-parallel, HITRAN-based gas absorption

Heating rates: Comparison of “uncorrelated “ k-binning MOMO and RRTMG

TOA fluxes across cloud experiments:

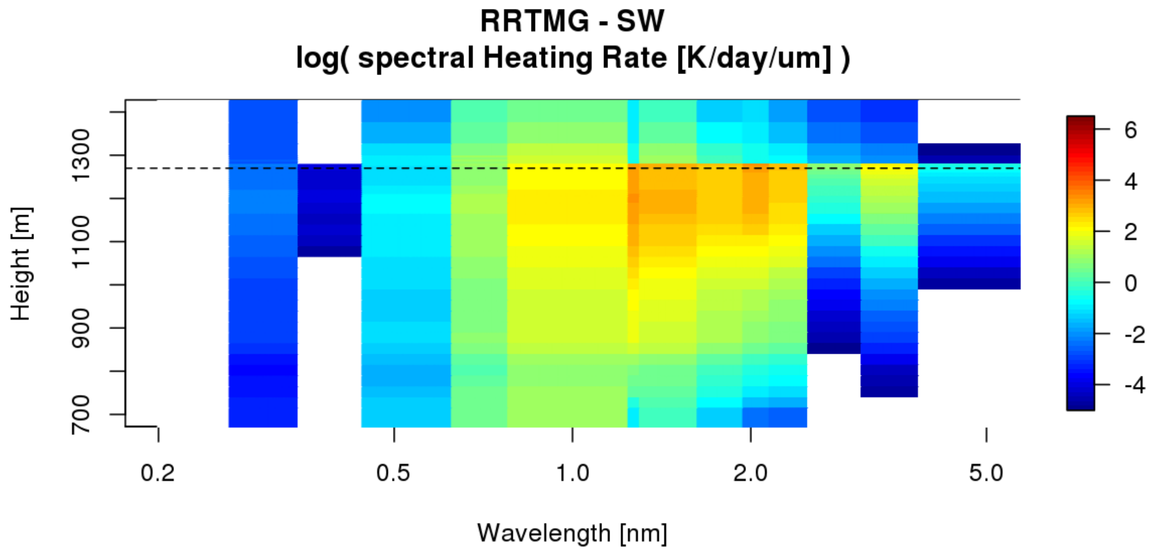
- SW fluxes with similar sensitivity, just within 10 W/m²
- LW fluxes different in sensitivity, yet within 1.5 W/m²

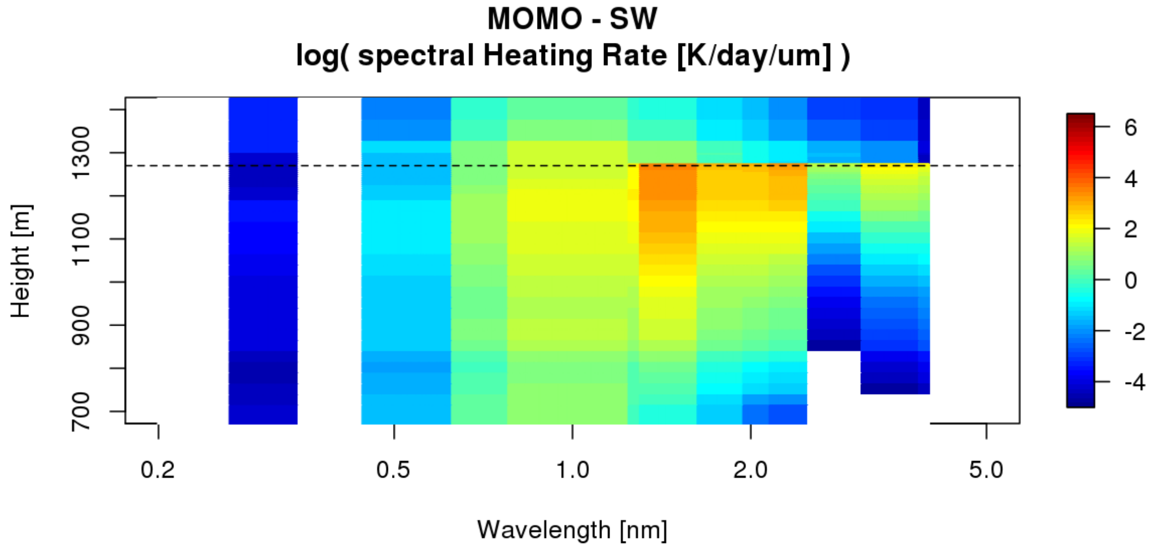


Heating rates: Comparison of “uncorrelated “ k-binning MOMO and RRTMG

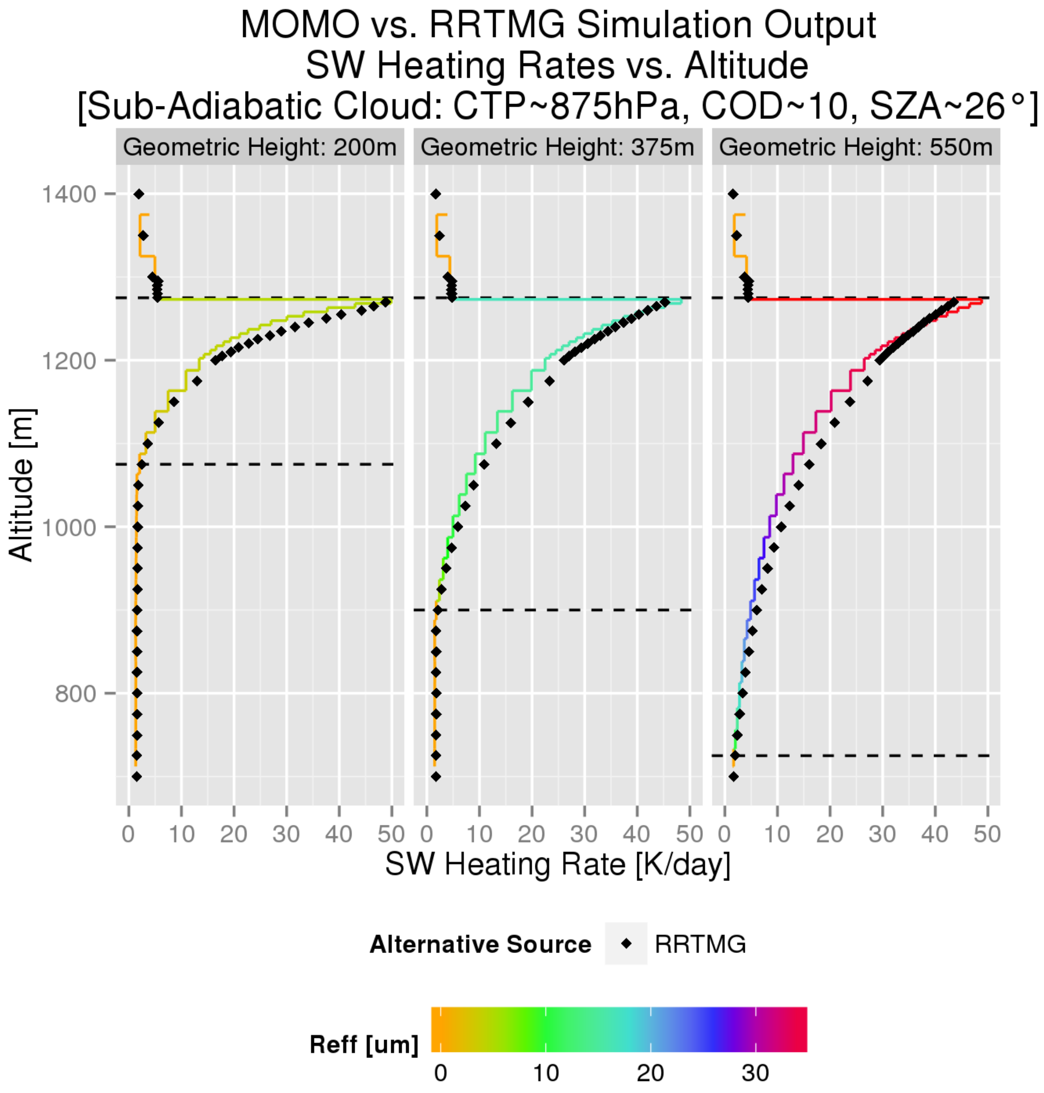
SW heating rates:

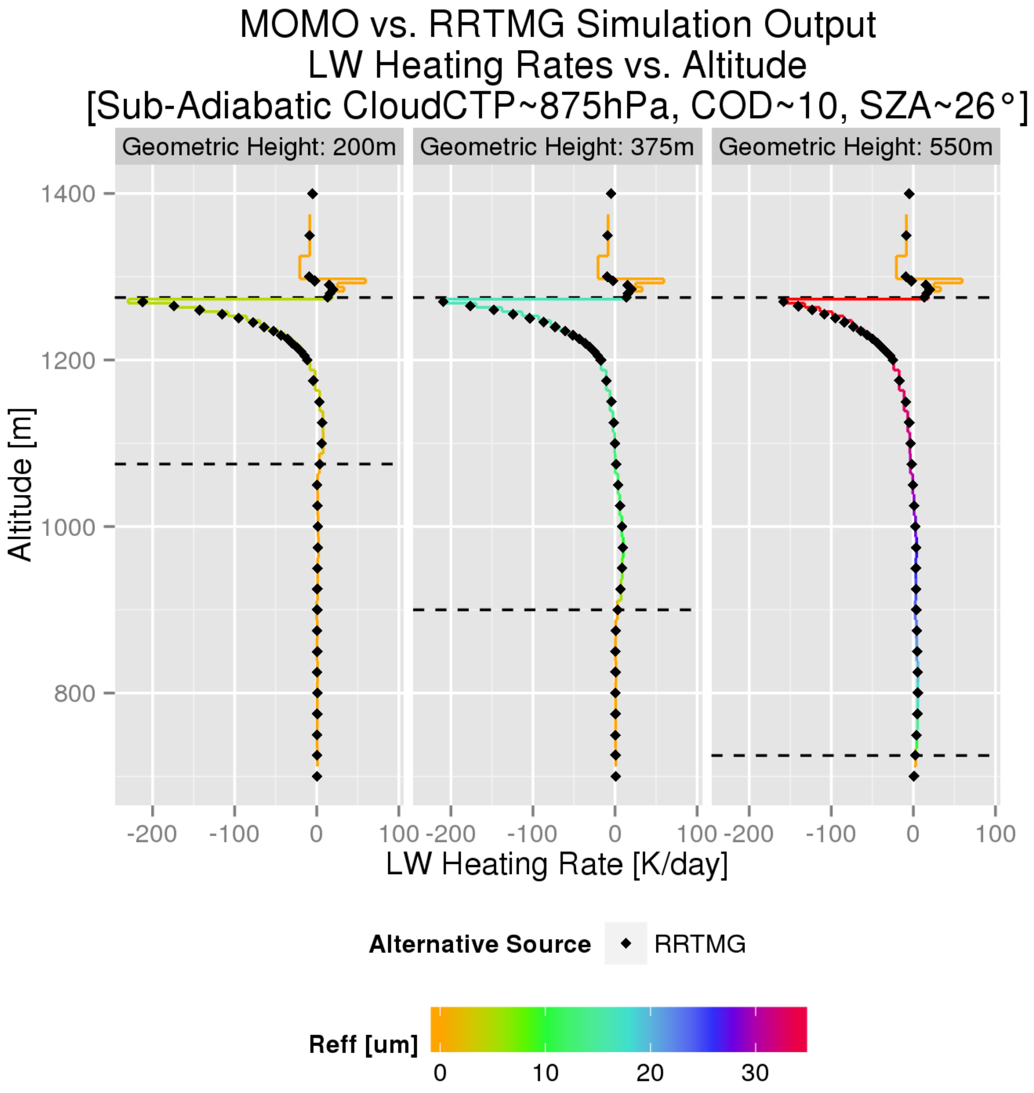
- similar response to cloud properties
- RRTMG with less absorption at cloud-top:
  - MOMO with enhanced water-vapour absorption due to multi-scattering
  - clear-sky water-vapour absorption agrees quite well


RRTMG - SW
log(spectral Heating Rate [K/day/um])


MOMO - SW
log(spectral Heating Rate [K/day/um])

Heating rates: Comparison of “uncorrelated “ k-binning MOMO and RRTMG


MOMO vs. RRTMG Simulation Output
SW Heating Rates vs. Altitude
[Sub-Adiabatic Cloud: CTP~875hPa, COD~10, SZA~26°]


MOMO vs. RRTMG Simulation Output
LW Heating Rates vs. Altitude
[Sub-Adiabatic CloudCTP~875hPa, COD~10, SZA~26°]

Conclusions: K-binning

- Correlated K-distribution methods are sufficient to picture the **total transmission** due to atmospheric gaseous absorption
- Un-correlated K-distribution methods are sufficient to picture the **total transmission and the layer transmission** due to atmospheric gaseous absorption
- Un-correlated K-distribution methods provides higher accuracy since it takes care of the different line shapes within different atmospheric layers
- Un-correlated K-distribution provides sufficient accuracy depending of the number of k-binning terms

Conclusions: Applications

- The broader the spectral “bands” the less k-binning terms are needed (at least in most of the cases !)
- Satellite spectral measurements should be simulated by uncorrelated K-distribution methods, depending on the required accuracy (assimilation).
- Un-correlated K-distribution method, used by MOMO differs by
  1.5 W/m2 in the longwave
  and
  10 W/m2 in the shortwave
  when compared to much more simplified RRTMG.