Authors responses to Atmos. Meas. Tech. Discuss., https://doi.org/10.5194/amt-2019-282

kCARTA : A fast pseudo line-by-line radiative transfer algorithm with analytic Jacobians, fluxes, Non-Local Thermodynamic Equilibrium and scattering for the infrared

by DeSouza-Machado et. al.

We thank the anonymous referees for their detailed read of the paper and providing introspective comments, many of which have resulted in changes to the revised version of the manuscript. In particular we have improved the accuracy of the computed kCARTA radiances by changing our default options (now linear-in-tau, higher resolution spectral database in the 15 um region). This update has already been pushed to github. We have also shortened the paper by removing the sections describing comparisons between the HITRAN/GEISA/CO_2 line-mixing databases, and the impact of spectroscopic uncertainties on TOA radiances. This has been replaced by a section where we compare kCARTA versus LBLRTM TOA radiances.

Below we detail our responses to their individual concerns. For ease of review, we type-faced the reviewers questions in blue. When we refer to pages and line numbers in our answers, the context should make it clear whether we are talking about the original manuscript or our current revised manuscript.

Reviewer 1

Specific comments

1) There is no comparison of kCARTA radiances with a more well-established (and preferably line-by-line) model, not even the source models UMBC-LBL or LBLRTM. The kCompressed tables have been previously verified to reproduce the absorption coefficients or optical paths, but this paper deals with all the extra components of a radiative transfer model.

We have added a section that describes detailed inter-comparisons against LBLRTM.

2) I have concerns about the impact of the coarse spectral resolution: 0.0025cm-1. Where does this figure come from? The usual requirement for radiative transfer is to be able to capture the signal from Doppler-broadened lines in the upper stratosphere, which have typical mid infrared widths of 0.001 cm-1, hence resolutions of 0.0005 or 0.001 cm-1 are generally considered necessary. Given the inherent flexibility of the kCompressed tables, I am also surprised that the authors have not considered using an adaptive, rather than fixed, spectral grid, so that the spectral resolution is concentrated around the line-centers, so obtaining better accuracy for the same size compressed datasets and computation time.

As clearly stated in the title and abstract of the manuscript, kCARTA is a pseudo (monochromatic) line-by-line code, written specifically to compute radiances which are accurate when convolved with the Spectral Response Functions of the new generation of hyperspectral nadir sounders (or larger than 0.1 cm^{-1} resolution). The loss of information due to compression with a finite number of basis vectors, means that for some molecules with complicated lineshapes we cannot completely reproduce the true monochromatic optical depths. However after convolution with a typical sounder response functions (resolution typically 0.5 cm^{-1} at 15 μm), kCARTA is shown to easily compute accurate radiances (especially keeping in mind the large spectroscopic uncertainties that still exist in CO_2 line mixing, and larger detector NeDT at the long wavelengths, see for example Figs 3,4,5 of the original manuscript). We have re-written parts of the Paragraph 1, Page 2 to emphasize this.

We also thank the reviewer for pointing out we can easily improve kCARTA inter-comparisons against for example LBLRTM by changing the defaults to be (a) linear-in-tau and (b) higher resolution at the 15 μm region (605-880 cm^{-1}). The above mentioned additional section will demonstrate we have tested and implemented this; any user interested is using higher resolutions can easily do so, by generating the appropriate database.

We have previously explored constructing and using databases of lower resolution in the lower atmosphere, and gradually increasing the resolution as the layer pressure decreases, but we found that while we could retain the TOA accuracy, the code was slowing down. More importantly the SVD compression works best

with single resolution. The compressed files are small enough that it does not matter if the resolution is higher than needed in the troposphere.

3) I am unclear on the conversion of atmospheric profile quantities (temperature, pressure, composition) to the (presumably?) equivalent homogeneous paths represented by the kCompressed data. Are these absorber-weighted equivalent (ie Curtis-Godson) temperatures and pressures? Or simply layer means? Given the use of a spherical atmosphere (what radius of curvature is assumed?) rather than a plane-parallel assumption, presumably some sort of numerical integration scheme is required to obtain these quantities, even the total amount of absorber in a layer.
Line 455 of the original manuscript states that our kLAYERS program takes in n-level point profiles (typically pressure, temperature, water vapor and ozone profiles), interpolates these points onto a fine grid and then integrates to produce the final integrated layer output profiles for the gases (in molecules/cm2) and one average temperature (same for all gases) at each of the AIRS 100 layers. We wanted to define one layer temperature for all gases, as kCARTA (and SARTA) are used for atmospheric retrievals. Furthermore kCARTA is effectively monochromatic, so does not need Curtis-Godson temperatures.
Internally kCARTA does have the ability to use individual (Curtis-Gordon) gas temperatures at each layer, but those need to be provided as input.
The kLAYERS program uses Planet Earth parameters (radius and height dependent gravity), and also adds in the variable trace gas profiles as needed (such as CO_2, CH_4, CO). The kCompressed database is saved at the same AIRS 100 layers, so the default kCARTA ingests the output of kLAYERS, un-compresses the database and does the radiative transfer.

4) Section 4, on the impact of spectroscopy on TOA radiances, seems an unnecessary digression. While spectroscopic uncertainties are certainly an issue that merits attention, that's not really anything to do with the kCARTA model being introduced (besides which all the variation is handled in the generation of the kCompressed datasets, which are to some extent independent). The data gap in the plots, arising from the gap in AIRS coverage, is also undesirably for such a comparison. It would have been more useful to see comparisons of kCARTA TOA radiances against other models instead.
Showing TOA BT uncertainties due to spectroscopy is very important, both for scientists working on retrievals and for those working on data assimilation. To our knowledge this assessment has not been documented (at least recently). However we agree it is an unnecessary digression in this paper, and have removed the entire Section 4 of the original submission.

5) For most molecules, kCARTA uses data created by the UMBC-LBL model using the Van Vleck and Huber lineshape. Since the Voigt lineshape is very much the 'standard', there should be some explanation of how this differs and why it is used in preference to Voigt.
UMBC-LBL is based on GENLN2, which also uses the Van Vleck/Huber lineshape. Initially used with Lorentz lineshapes to model microwave absorption, our implementation is a sum over two voigt lineshapes, one centered at v_0 and the other centered at $-v_0$. The VVH lineshape would have larger impacts for the microwave regions; for the infrared wavelengths considered here the second term is negligible and it is essentially the Voigt lineshape.

6) The inclusion of non-LTE effects, just for the CO2 4um band, seems to require the inclusion of a separate line-by-line model within kCARTA. This is a huge overhead in complexity for a relatively specialized application. Given the kCARTA structure, it seems a more natural approach would have been to incorporate vibrational temperature as an extra axis on the kCompressed datasets, and just use GENLN2 to calculate these. Alternatively, if you are including a LBL model within kCARTA, at least extend it so that LBL (with or without non-LTE) can be used for any molecule.
We have already included links to our monochromatic (Matlab based) LBL code. For nadir sounders that kCARTA is designed for, we only need 4 μm CO_2 NLTE effects where the different vibrational temperatures means we need to account for both the changes in optical depths and for the modifiers to the Planck function. The exisiting code inside kCARTA can compute both NLTE and LTE effects (for the 4 um CO_2 lines for which we include line and line-mixing parameters), but since we do not use accelerated Voigt functions or continuums, using it for all molecules would unnecessarily slow down kCARTA. We have explored making a NLTE compressed look-up scheme for kCARTA, for both the optical depths and

multipliers to the Planck function. However we did not get satisfactory results, and left this as a "to be revisited someday" project.

7) The calculation of background thermal radiation (section 7) uses an interesting idea, and would probably have merited some expansion as a separate (if somewhat specialized) article by itself. I have a number of questions, detailed in the minor comments
We have answered those questions.

TYPOS/MINOR COMMENTS

P1 L20: '... data are presently ...'
Fixed

P1 L20: Given Susskind was describing cloud clearing for the previous generation of meteorological instruments I'm not sure it's an appropriate reference for the hyperspectral instruments.
The previous generation of weather sounders included HIRS. AIRS is the first of the new generation of hyperspectral sounders. The referenced 1998 Susskind paper is the most relevant reference for operational cloud clearing, and it discusses retrievals using simulated AIRS spectra.

P1 L20: The text may be read as implying that there is some sort of correction applied to the spectra to remove the influence of clouds, whereas I suspect it is more accurate to say that any cloud-contaminated spectra are simply rejected.
With $\sim$ 15 km footprints, less than 4% of current hyperspectral sounder observations can be identified as mostly cloud free. The $\geq$ 60% global coverage retrieval yield of the operational NOAA CrIS NUCAPS and NASA AIRS L2 retrievals is achieved by explicitly using cloud cleared radiances.

P2 L27: What determines this 0.0025cm-1 figure? As a rough estimate I expect it would be determined by the requirement to resolve the Doppler widths of lines, and given molecular velocities are of the order of c/10^6 that would correspond to around 0.001 cm-1 at 1000 cm-1.
As noted at the beginning, and is explicitly part of the new Section 7 in the revised manuscript, the key requirement is that the monochromatic kCARTA radiances can be accurately compared to any real (or hypothetical) sounder radiance. This is achievable using a database generated at 0.0005 cm^{-1}, five point box car generated to 0.0025 cm^{-1}. However to further improve the accuracy, we have changed the resolution of kCARTA to be 0.0005 cm^{-1} in the 605-880 cm^{-1} cm-1 region. If required kCARTA can easily switch to use higher resolution databases across any spectral range, which now are much faster to generate.

P2 L27: I am not convinced by the argument that the computation of optical depths at high spectral resolution for 50 or so profiles for the training set is something that needs accelerating. Surely this is something that only has to be done once and, even if occasionally repeated, the fact that it takes a week rather than a couple of hours isn't really be an issue.
Our historical motivation has been further explained in Q2 above. kCARTA is also used to check the newly developed (and/or existing) fast model against tens of thousands of other regression profiles we have, as well as tens/hundreds of thousands of AIRS, CrIS and IASI observations as needed. All this can be done extremely rapidly in an embarrassingly parallel fashion with kCARTA. We also generate monochromatic jacobians and weighting functions for some of these observations or test profiles, which for the 605-2830 cm^{-1} region can be done by kCARTA in less than two additional minutes per profile.

P2 L40: I assume the issue with replacing line-by-line with kCompressed data is one of the accuracy of the absorption coefficient or reconstructed layer optical depths. However to state that the 'radiances' are accurately reproduced requires a whole new set of tests to verify the accuracy of the radiative transfer through an atmosphere.
Our 1998 paper stresses we tested the accuracy of the reconstructed radiances against those computed using the uncompressed monochromatic tables. Plus we regularly perform a number of tests offline, involving both single gas and multiple gas radiative path integrals. We hope answers/revisions made to the manuscript further address some of this.

P2 L49: Missing second ')' after 1999.

Fixed

P3 L71: I have not come across the Van Vleck and Huber lineshape. Is this different to the more conventional Voigt? If so, how, and why the unconventional choice?
As explained above, for the infrared it is essentially the Voigt lineshape.

Fig 1: I appreciate this is just a sketch, but the black Total line doesn't seem to be a sum of the red, blue and green lines. Also raise the '-1' in the x-axis title to a superscript (and in subsequent figures).
We have fixed the xlabel here and in other places. Regarding the sums, we checked that everything is OK by modifying the code that generated this plot to print out the $y-$ values of the blue, green and three red curves at various points inside the $x \in (-0.5, +0.5)$ interval, the sum of these values, and the $y-$ value of the black curve, and verified they were identical.

P4 L98: Regarding MonoRTM - what is the point being made here?
Our understanding is that monoRTM is the reference line-by-line code which LBLRTM is checked against. So, our compressed ODs are as accurate as the monoRTM ODs (at least for 10 um O_3 absorption spectrum), and we are confident the Van Vleck/Huber lineshape in the UMBC-LBL code will work just as accurately when used for appropriate molecules in the IR region (this would obviously not be true for molecules that use specialized lineshapes, such as CO_2 and CH_4 linemixing). Since that point did not come across clearly, and is not really needed, we have removed it.

P5 L107: +/- 50K does not seem a large range in temperature. Do you have any evidence that it spans the full range of atmospheric variability?
We read in one set of ECMWF data for 2019/08/01 (360x180 one degree grid points) and ran the $\sim$ 64000 profiles through kLAYERS. All but 4% of the temperature profiles lay within $\pm$ 50 K of the US Standard temperature profile. The ones that lay outside these bounds were all profiles over the Antartic plateau, on average 3 $\pm$ 2 K outside the -50 K offset (between 500 - 1000 mb). kCARTA handles these cases by extrapolating compressed ODs (and zero checking) as needed. We have added this information into the appropriate place of the revised manuscript using the following phrases "Tests using NWP profiles show this is usually sufficient everywhere except for a handful over the winter Antartica, which could fall slightly outside the coldest offset (on average by about 3 K) between 600-1000 mb; kCARTA handles these cases by extrapolating what has been compressed."

P5 L108: 'contains'
Fixed

P5 L122: HITRAN 2016 lists two further isotopologues for water vapour containing a single deuterium atom and either a 17O or an 18O oxygen isotope (these are HITRAN isotopologues 5 and 6). Are these included with HDO or with the remaining H2O isotopologues?
With the remaining H2O isotopologues

P6 L144: It is not clear why the cross-section molecules are also represented using kCompressed databases. Presumably these end up much larger than the original files, which usually have only a few tens of (pressure,temperature) points and a much coarser spectral axis. Also using CIA probably won't work with LUTs - how will these new data be used?
We chose to do it this way in order to compute the ODs of all gases (molecular and cross-section) equally. In any case our database size is dominated by the main molecular gases (H_2O, CO_2, O_3). The CIA is handled by calling the necessary routines within kCARTA.

P6 L150: HITRAN 2016 lists 49 rather than 42 molecules, and a number of these (or even 1:42) are not represented in the US Standard Atmosphere.
Correct, we only use the first 42 as we were able to get the "standard" or "realistic" profiles for them; similarly now HITRAN has very many cross sectional profiles but we only use the ones for which we are able to find representative profiles in the scientific literature.
We have amended the sentence to read "The default kCARTA mode is to use the 42 molecular gases in HITRAN database, together with about 30 cross-section gases, for which we have reference profiles. "

P6 L158: 'Schwarzschild'
Corrected

P7 Eq(3): The solid angle integration should just be over a hemisphere and should include the B.dt/ds term scaled by cos(e) where e is the elevation angle 0:pi/2 in the hemispheric integration (thus the integral of cos(e).dOmega from 0:2pi on its own should yield pi).
Both fixed, thanks for pointing out these mistakes

P7 Eq(3): I don't see why the cos(theta_sun) appears in the last term on its own, but it seems there should be some solid angle integration over the sun's disk (as in Eq 6) otherwise it will be as if the whole sky radiates at the solar temperature.
The manuscript has defined $B_{\odot}(\nu)$ as the solar radiance at the TOA, so that accounts for the solar disk.

P7 L170: Isn't 1-epsilon_s(nu) the same as rho_s(nu)?
Default behavior of kCARTA is to do this; however we can explicitly input reflectivity so that we could for example handle sun glint off an ocean

P7 L171: extra comma near end of line
Fixed

P7 L171: There is no tau_i term in Eq(3), just tau and tau_atm.
Fixed

P7 L180: Assuming the temperature profile is specifed at points P,H1,H2 etc what constant temperature is assumed for, eg the lowest layer? Is it T(P), T(H1), or something else?
Already answered above when we respond to the question regarding use of kLAYERS; it is the layer averaged temperature for the layer between P and $H1$

P7 L182: By 'density effects' do you mean refraction?
Correct

P7 L186: Both emissivity *and* reflectance have to be supplied? Eq(4) only uses emissivity.
Yes, Equations (3,6,7) shows that kCARTA also uses reflectivity. We have amended both sentences in that and subsequent sections to make it more clear.

P8 Eq(5): The indexing doesn't seem to work. Interpreting tau_(i+1 to N) as the transmittance from the base of layer i+1 to the base of layer N the calculation for layer 3 in the diagram would be (1 - tau_3).tau_(4 to N) but here N=4 so tau_(4 to N) = 1 whereas it should be the transmittance through layer 4. Similarly Eqs 8-10
We see the confusion has arisen because we forgot to state that (a) τ_i represents the transmission through layer i (i.e. from bottom to top of layer i), and that (b) $\tau_{i+1\rightarrow N}$ is the transmission from bottom of layer i+1 to top of layer N. So we have taken the opportunity to add in these definitions and make some additional clarifications in the relevant text/equations.

P8 L195 Better to swap sections 3.3 and 3.4 to match the same order these terms appear in Eq (3)
Done

P8 L196 rho is now defined as reflectance, but for Eq 3 it was reflectivity. Is there a difference?
We now consistently use reflectivity everywhere, instead of reflectance.

P9 L213 As a general comment, it would be nice to have a plot of the magnitude of these four terms as a function of the infrared spectrum, assuming say some fixed surface emissivity of around 0.98 (so 2% diffuse reflectance).
We added in a number of figures detailing the comparisons against LBLRTM, and decided not to do this.

P9 Section 4: Presumably for this exercise different sets of kCompressed databases were computed by running UMBC-LBL etc for the different sets of spectroscopic data, and then running kCARTA using these 3 different sets of kCompressed databases. If one really wants to demonstrate the differences in TOA

radiance couldn't one simply run the LBL models with the different spectroscopic data and eliminate the whole intermediate step of generating kCompressed datasets?
We re-iterate that running the UMBC line-by-line code which does not use acceleration for the Voight fucntion and/or gas continuums is very time consuming, as it partitions the lines into "near" "medium" and "far". This has to be done molecule by molecule, layer by layer, across the entire 605-2830 cm^{-1} spectrum. This is a significant amount of time even if computed in embarrassingly parallel mode. Our 1998 JQSRT paper already shows how accurate our compressed database is. This means once the compression is done, kCARTA can be used to generate synthetic radiances for thousands of NWP model atmospheres in a number of minutes (when kCARTA is used in embarrassingly parallel mode).

P9 L230 'linemixing'
Fixed

P10 L243 'sagain' ?
Replaced with "panel"

P10 L247 it is not clear that differences have anything at all to do with linemixing - it seems they might simply reflect differences in the standard line widths that would be evident whether line-mixing effects were included or not?
That is possible, but we cannot exclude that differences in mixing coefficients determine how much intensity has to be transferred from the wings to the peaks. We have not investigated that idea as for now we have chosen to simply use available CO2 codes. A proper test would involve using other line-mixing codes together with different spectroscopic databases, but that is outside the scope of this paper.

P13 Section 5: It seems odd that kCARTA has a non-LTE line-by-line module - it is something I would have expected in the UMBC-LBL code. Have you considered modelling non-LTE using kCompressed datasets? That would seem more in keeping with the overall design. Perhaps you would need an extra tabulated dimension in vibrational temperature, or (vib-kin) temperature?
Our line-by-line code could indeed be modified to generate the ODs using the vibrational temperatures. However NLTE also effects the Planck function and we would also need to compute the multipliers to the Planck function and give them to kCARTA. For these and other reasons it is more natural to put the NLTE effects directly into the kCARTA RTA. As explained above, generating compressed lookup tables for NLTE effects remains a "to be revisited someday" project.

P13 Eq 9: Summations should be from i=1,N. Also, tau_(i+1 to N) in second summation should have (nu) afterwards.
Fixed

P14 L304: 'Jacobian' from here to the end of the section start to be capitalised - inconsistent with earlier 'jacobian'
Fixed everywhere

PP14 L305: How is dB/dT calculated? (where s_m = T_m).
Analytic derivative of the Planck function

P14 L310: I don't understand the last sentence - what's the difference between the Jacobian and the weighting function wrt surface temperature and emissivity?
We have rewritten the sentence to state "kCARTA also computes the weighting functions, and jacobians with respect to the surface temperature and surface emissivity."

P14 L320: 'contributes'
Fixed

P15 L334: the dmu should come after the exp(-x/mu).
We have moved $\mu d\mu$ after the $exp(-x/\mu)$

P14 L334: Is there any significance in labelling this integral as E_3 ?
It is the exponential integral of the third kind, and have added this to the text.

P14 L334: No closing bracket to match '('.
Fixed

P14 Eq 13: From discussing downward radiation, the introduction of reflectance rho_s suggests to me that you are now modelling the reflected component of this radiance just above the surface. Where does the 2pi come from? I think you need to explain some of the intermediate steps.
Assuming azimuthal symmetry when doing the hemispheric integral gives the factor of 2π.

P14 L340: If I understand this correctly, instead of approximating the downwelling radiance as if it comes from a fixed angle cos=3/5, you are adjusting the angle for each atmospheric layer according to the surface-layer optical thickness x. It would be nice to see some plots of the comparisons with a full hemispheric integration to show that this is sigifnicantly more accurate than the fixed angle assumption. Also, is there a reason why the cut off at 30deg has to be applied for optically thick atmospheres? Otherwise it might also be useful for modelling the radiance viewed by upward-looking instruments, or downward looking instruments close to the surface.
LBLRTM does flux calculations at 3-4 gaussian quadrature angles, which is evidence that a single angle asumption is not accurate enough. Instead of this, we chose to do downwelling background thermal using a varying diffusivity angle at each layer. For optically thick regions, a TOA sounder is not going to remotely sense any contribution from the surface, whether it is directly emitted by the surface or reflected from the surface. Hence, in these regions there is no need to calculated the background thermal at all. We agree that for the more transperant regions, a little more care should be taken for downward looking instruments close to the surface, including a finer layering of the atmosphere closer to the surface, which kCARTA and kLAYERS can both handle, as discussed in the 1998 paper.

P15 L346: Given the rapid spectral variation in any 25cm-1 interval, I don't understand how you can assign a single assumption to the whole interval. Won't there be a whole range of optical thickness within the 25cm-1 region so that the assumption works better for some spectral points than others?
Both the lines and wings of an optically thick region are mostly opaque i.e. you do not go from transparent to optically thick in a few tenths of a wavenumber, but rather over an appreciable interval. So encompassing 25 cm^{-1} chunks as we did is fine. Furthermore we have tested our assumption against Gaussian quadrature, and our method is far superior to simply using acos(3/5) for downwelling radiation. The user can also opt to use only acos(3/5) or do Gaussian quadrature.

P15 Sec 7.2: The linear-in-tau model, where optical depth is scaled by the sec(theta) to allow for off-nadir viewing angles, assumes a plane-parallel atmosphere where theta is fixed for the layer (and the same for every layer). How is this handled for the spherical atmospheres assumed in kCARTA where cos(theta) can vary significantly when viewing off-nadir?
kCARTA defaults to dividing an 80 km thick atmosphere into about 100 layers, with the layers starting out being about 0.25 km thick at the bottom, and gradually increasing in thickness the higher you go. The linear-in-tau models the temperature variation through each of the individual layers. So kCARTA does linear-in-tau T(tau(i)) at angle theta(i) the same way as it does constant T(i) at angle theta(i) : by varying the angle layer by layer as the beam propagates upwards.

P16 L365: It depends what you mean by the 'average layer temperature'. For the optically thin limit you would expect this to converge to the Curtis-Godson temperature, ie the absorber-weighted mean temperature, which would generally be at an altitude below the layer mid-point.
As explained above, we accurately determine the mean layer teperature using kLAYERS, and then use the definitions in the Clough et al 1992 JGR paper to determine the temperature variation across the layer.

P16 L377: Even though it largely disappears after convolution (presumably because the AIRS spectral resolution means that the radiance is dominated by contributions from lower altitudes), this 10 K difference does seem to be a serious issue. And one which would limit the use of kCARTA for accurately representing finer resolution instruments. Is this really due to not implementing linear in tau or could it be that kCARTA only uses a crude representation of layer temperature rather the something more physically justified such as Curtis Godson temperature? Why doesn't kCARTA just use the linear-in-tau model?
Given an input temperature profile, kLAYERS internaly interpolates to a fine grid before accurately finding

the mean layer temperature. We do not need a Curtis-Gordon temperature since at each wavenumber point we are essentially monochromatic (not a band model). It is also well known that hyperspectral sounders have at most about 12-15 degrees of freedom for temperature, so our 100 layers are more than adequate. We also input the kLAYERS temperature profile into the LBLRTM TAPE5, and as far as we can tell it is then not using a more physically justified temperature than kCARTA does.
As mentioned in the title and at the beginning of the answers, kCARTA is a pseudo (monochromatic) line-by-line code. The large (10+ K) differences are seen when comparing kCARTA to LBLRTM at 0.0025 cm^{-1} resolution, since the latter internally is doing the upper atmosphere calculations at high resolution. As we improve the kCARTA database resolution, the differences become significantly smaller. For example if we use 0.0002 cm^{-1} resolution, it drops to less than 1 K $\pm$ 1 K right on top of the high altitude 15 μm CO_2 lines, and -0.1 $\pm$ 0.05 K in the high altitude O_3 sounding channels, when averaged over our 49 regression profiles. If we use 0.0005 cm^{-1} resolution, the 15 μm/10 μm numbers are correspondingly 4 $\pm$ 1 K and -0.3 $\pm$ 0.1 K. After convolution with a sounder SRF, the differences are neglible. As mentioned earlier, we thank the referee for pointing this out to us and have made 0.0005 cm^{-1} the default resolution in the thermal IR; any interested user can easily generate and use a higher resolution grid if desired.
We note that it appears that we run into slight differences in CO_2 line broadening and/or resolution right on top of the lines, and perhaps algorithm differences (LBLRTM may use a Pade approximation and/or Eqn 15/16 to first order while we use Eqn 16 to fifth order).
The above evidence provides ample confidence that the linear-in-tau RTA is working quite well, even when allowing for ray tracing. As expected after convolution with a sounder SRFs, these differences mostly vanish, since these differences are right at the peaks of a small number of very high sounding CO_2 lines.
This is all described in the (new) section 7, on inter-comparing kCARTA and LBLRTM. We note this meant we also had to change a few sentences in the section on flux computations, and in Appendix B.
kCARTA now uses the linear-in-tau model.

P17 L390 'computes'
Fixed

P17 Flux Computations: are these with spherical or plane-parallel atmospheres?
Whether you use the (exponential or legendre) gaussian quadrature, we use the same fixed quadrature points at each layer so that is plane parallel.

P17 L407: Given the differences found from the linear-in-tau model in the previous section, could the differences in heating rates at high altitude simply be another manifestation of the same problem, ie assumption of constant temperature within thick layers at higher altitudes?
We believe our above responses above adequately address this issue, namely it is the resolution. In addition we have stated when doing flux computations, kCARTA uses linear-in-tau.

P18 Fig 6 caption: should be '0.0005' instead of '0.005'.
Fixed

P18 L425: 'accuracy of its spectroscopic database'. I assume this refers to the kCompressed tables used as kCARTA input as opposed to the usual meaning which would be HITRAN or GEISA spectroscopic databases. But comparisons against GENLN2 or LBLRTM wouldn't just be a comparison of the kCompression with the original HITRAN unless your tests were for simple homogeneous paths where transmittance could be verified independently of other model assumptions such as ray-tracing and integration through atmospheric layers.
Correct we are referring to the accuracy of the compression.

P19 L434: '0.0025 cm-1 is good enough for nadir hyperspectral sounders' - this is a contentious statement, and needs some justification (there is none in this paper).
We are confident our responses to the earlier questions address this issue, especially in light of the fact that most residuals are far smaller than detector NeDT when the radiances are convolved with realistic sounders response functions.

P21 Table B2: lists (6) Direction as downwelling by default, upwelling as an option. Isn't it the other way

around?
Corrected, thanks for pointing this out

P22 L488: extra ')'.
Fixed

P22 L495: 'up to'
Fixed