Response to J. Wang's interactive comment on **"Intercomparison of shortwave radiative transfer schemes in global aerosol modeling: results from the AeroCom Radiative Transfer Experiment"** ***by*** **C. A. Randles et al.**

The manuscript presents the intercomparison of ~30 shortwave radiative transfer models in the context of AeroCom and aerosol forcing estimate. The results are analyzed in terms of model diversity w.r.t. LBL benchmarks for three cases at two solar zenith angles (30 and 75 degrees): (1) gas + Rayleigh, (2) gas + Rayleigh + scattering-only aerosol, (3) gas + Rayleigh + absorbing aerosol.

The authors find that different RTMs can yield 10-20% difference in forcing estimates, but those RTMs with two stream scheme generally have larger biases. In addition, the model diversity is found to decrease for absorbing aerosols, further suggesting that multi-scattering should be carefully treated. The biases in RTMs are found to vary with solar zenith angle, which may introduce systematic errors in the estimate of regional and seasonal forcing of aerosols.

The manuscript overall is well written, although I felt more discussions about the implications of the findings from this manuscript are needed. I provide a few comments/suggestions in below. Overall, I am looking forward to seeing this manuscript appear in ACP soon.

We thank Prof. Wang for his thoughtful comments regarding the manuscript. Below we address, in bold, general and specific concerns.

1. *Radiative forcing varies non-monotonically with solar zenith angle. Russell et al. (1997) showed that forcing may have maxima around solar zenith angle of 60. This non-monotonic feature should be recognized and considered in the interpretation of the analysis here (that is from two angles only). Not sure why solar zenith angle of 75 degrees is selected?*

Russell, P. B., S. A. Kinne, and R. W. Bergstrom (1997), Aerosol climate effects: Local radiative forcing and column closure experiments, J. Geophys. Res., 102, 9397–9408.

We agree with Prof. Wang regarding the variation of forcing with solar zenith angle. In our study, we adopted the protocol of a previous RTM inter-comparison study (i.e. Halthore et al., 2005), which considered SZA of 30 and 75 to provide a range of conditions representative of tropical and high-latitude locations, respectively. A SZA of 60 would be characteristic of mid-latitude conditions, and we did not consider this zenith angle (1) for simplicity (i.e. keeping the number of calculations manageable); and (2) because the companion AeroCom papers (Stier et al., 2013 and Myhre et al., 2013) implicitly address SZA variations by focusing on global average comparisons of aerosol radiative forcing. Additionally, 2-stream models generally compare better with multi-stream models at SZA 60 than at the angles considered in this study.

We do agree that our choice of zenith angles warrants further discussion, so we include the following text in the concluding remarks (fifth paragraph, added text is underlined):

"<u>In this study, we considered solar zenith angles more representative of the tropics (30°) and high latitudes (75°) following Halthore et al. (2005). A previous study (Russell et al., 1997) indicated that aerosol radiative forcing may peak somewhere in between these angles (specifically, around 60° for mostly scattering aerosol due to the competition between path length and available sun energy). Thus, biases reported in this study may be mitigated in the global average.</u> Indeed the inter-model diversity reported in this study for the two specific zenith angles is generally higher than those reported for global, diurnally-averaged conditions (Myhre et al., 2013) even when the same aerosol optical properties are prescribed (Stier et el., 2013). <u>Though biases may be larger when considering specific zenith angles</u>, we note that all three AeroCom studies indicate decreased inter-model diversity in atmospheric radiative forcing as aerosol absorption increases. Further, both Stier et el. (2012) and this work show that atmospheric absorption is enhanced when considering scattering-only aerosol because the increased photon path-length increases molecular absorption, particularly by ozone."

2. *Despite this is a modeling exercise, it might be good to talk about the implications of findings of this paper to what is needed in the observations to constrain the model estimate of forcing. For example, since forcing bias is sensitive to solar angles, will measurements of diurnal variation of aerosol properties and upwelling flux from geostationary satellite be helpful? Such discussion will be valuable for current planning for future satellite missions that need inputs and recommendations from modelers.*

We find this to be an excellent suggestion, and we include the following text in the concluding remarks (final paragraph):

"This study has presented an inter-comparison of radiative transfer schemes used in global aerosol modeling using common idealized aerosol properties. We have shown that, assuming aerosol properties are perfectly known, the bias in aerosol radiative forcing is sensitive to the solar zenith angle. Yet, it is expected that inter-model differences in simulating aerosol properties (e.g. AOD, SSA) would likely introduce biases in radiative forcing of greater magnitude than presented here. Global observations of AOD have served to reduce inter-model diversity in simulated AOD (e.g. Textor et al., 2006, 2007). An observing system that helps to better constrain the diurnal variation of aerosol optical properties would enable global aerosol models to converge to a better representation of these properties as a function of zenith angle and hence a better estimate of aerosol radiative forcing. The smaller biases introduced by the use of two-stream radiation schemes can be mitigated by future advances in computational power

that will allow multi-stream schemes to operate on-line within global aerosol models."

3. Trade-offs have to be made between # of the streams used in the RTM (e.g., speed) and the accuracy of the model. In addition, there are use of delta-scaling factor to better treat the phase function and obtain good accuracy that otherwise would need more number of streams in RTM. The speed can be a concern when comes to the global estimate of forcing. Can the manuscript have some discussions in this aspect?

We find this to be an excellent suggestion, and we include the following text in the concluding remarks (penultimate paragraph, added text is underlined):

"For daily forcing simulations, biases in radiative forcing indicate that there is a tendency by the two-stream models to under- and overestimate aerosol forcing for absorbing and scattering-only aerosols, respectively, at low latitudes (with predominantly low solar zenith angles during the day). At high latitudes (with predominantly high solar zenith angles during the day), scattering-only and absorbing aerosols both underestimate the magnitude of aerosol radiative cooling. <u>It is important to note that computational limitations often prevent the use of multi-stream radiative transfer schemes in global modeling. Delta-scaling serves to mitigate somewhat the accuracy sacrificed by two-stream models in their representation of the phase function.</u> Furthermore, from a climatological perspective, daily biases introduced by two-stream schemes may partially compensate one another when computing a global average radiative forcing. However, regionally and seasonally they may introduce systematic errors that can significantly impact aerosol climate effects."

Other minor comments:

1. Solar zenith angle and solar elevation angle are used in various places in the text. I would recommend using only one of them in the text to avoid inconsistence and inconvenience to the readers.

We have eliminated the use of "solar elevation" throughout the text and retain the use of "solar zenith angle."

2. Modeles in the appendix are arranged in alphabetical order, but then it is model # listed in table 1 that are used in the text . I find this is not convenient. When I read the text and find a specific model that I am interested to learn, I have to first go to Table 1, find & write down the name of the model, and then go to the appendix to find the right model in alphabet. why not just list the models in appendix according to their model #?

Table 1 was organized according to the type of multiple-scattering scheme, number of streams, and then gaseous transmission scheme. We originally ordered the Appendix in alphabetical order to avoid duplication of descriptions of, for example, the CAR models which are not ordered sequentially in Table 1.

However, we understand the inconvenience of this to the reader and now order by model number in the Appendix as well, with references to previous model numbers as warranted to reduce redundancy.