# Understanding top-of-atmosphere flux bias in the AeroCom Phase III models: a clear-sky perspective

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#### Abstract

Biases in aerosol optical depths (AOD) and land surface albedos in the AeroCom models are manifested in the top-of-atmosphere (TOA) clear-sky reflected shortwave (SW) fluxes. Biases in the SW fluxes from AeroCom models are quantitatively related to biases in AOD and land surface albedo by using their radiative kernels. Over ocean, AOD contributes about 25% to the 60°S-60°N mean SW flux bias for the multi-model mean (MMM) result. Over land, AOD and land surface albedo contribute about 40% and 30%, respectively, to the 60°S-60°N mean SW flux bias for the MMM result. Furthermore, the spatial patterns of the SW flux biases derived from the radiative kernels are very similar to those between models and CERES observation, with the correlation coefficient of 0.6 over ocean and 0.76 over land for MMM using data of 2010. Satellite data used in this evaluation are derived independently from each other, consistencies in their bias patterns when compared with model simulations suggest that these patterns are robust. This highlights the importance of evaluating related variables in a synergistic manner to provide an unambiguous assessment of the models, as results from single parameter assessments are often confounded by measurement uncertainty. We also compare the AOD trend from three models with the observation-based counterpart. These models reproduce all notable trends in AOD (i.e. decreasing trend over eastern United States and increasing trend over India) except the decreasing trend over eastern China and the adjacent oceanic regions due to limitations in the emission dataset.



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erences therein. The aerosol optical properties in OsloCTM3 are described in Myhre et
 al. (2007) with some recent updates, where the BC mass absorption coe cient (MAC)
 is following the formula in Zanatta et al. (2016) and a weak absorption implemented for
 OA (Lund et al., 2018).

# 637 Appendix B

Figure B1 shows the regional AOD biases of the AeroCom models relative to MISR 638 retrievals (left panels) and the regional SW ux biases due to AOD biases (relative to 639 MISR retrievals) and land surface albedo biases (relative to MODIS retrievals) calcu-640 lated from their radiative kernels (right panels) for April 2010. Many of the regional AOD 641 bias patterns shown here are very similar to the AOD biases shown in Figure 9. The SW 642 ux biases calculated from the radiative kernels using MISR AODs also resemble those shown in Figure 8. However, the biases over the tropical oceans are much muted when 644 MISR AOD is used. The correlation coe cients between F and  $F_{AOD}$  + F range 645 from 0.79 to 0.94 over land, which is very similar to those derived when MODIS AOD 646 is used. The correlation coe cients between F and  $F_{AOD}$  range from 0.26 to 0.63 647 over ocean, not as high as when MODIS AOD is used. The reduced correlation over ocean 648 is partly due to retrieval di erences between MODIS and MISR, but largely due to MISR 649 sampling issue as evident in the stripping features of the AOD bias plots. 650

## 651 Acknowledgments

All AeroCom simulations are available at the Norwegian Meteorological Institute. The CERES EBAF Ed4.1 data were obtained from https://ceres.larc.nasa.gov/data/. MODIS 495 MYD08\_M3\_0\_6\_1 550 nm AOD Dark Target+Deep Blue Combined data were obtained from the Giovanni online data system, developed and maintained by the NASA GES DISC. The V6 MODIS Bidirectional Re ectance Distribution Func- tion (BRDF)/albedo products (MCD43C1) were obtained from the Land Processes Distributed Active Archive Center (LP DACC) through https://lpdaac.usgs.gov/products/mcd43c1v006/.

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957	Wang, Z., Schaaf, C. B., Strahler, A. H., Chopping, M. J., Roman, M. O., Shuai,
958	Y., Fitzjarrald, D. R. (2014). Evaluation of MODIS albedo product
959	(MCD43A) over grassland, agriculture and forest surface types during dor-
960	mant and snow- covered period. Remote Sens. Environ, 140, 60-77. doi:
961	10.1016/j.rse.2013.08.025
962	Wielicki, B. A., Barkstrom, B. R., Harrison, E. F., Lee, R. B., Smith, G. L., &
963	Cooper, J. E. (1996). Clouds and the Earth's Radiant Energy System
964	(CERES): An Earth Observing System experiment. Bull. Amer. Meteor.
965	Soc, 77, 853-868.
966	Wild, M., Folini, D., Schar, C., Loeb, N. G., Dutton, E. G., & Konig-Langlo, G.
967	(2013). The global energy balance from a surface perspectiveClim. Dyn., 40,
968	3107-3134. doi: 10.1007/s00382-012-1569-8
969	Yu, H., Kaufman, Y. J., Chin, M., Feingold, G., Remer, L. A., Anderson, T. L., &
970	coauthors. (2006). A review of measurement-based assessments of the aerosol
971	direct radiative e ect and forcing. Atmos. Chem. Phys, 6, 613-666.
972	Zanatta, M., Gysel, M., Bukowiecki, T., N.and Meller, Weingartner, E., Areskoug,
973	H., Fiebig, M., Laj, P. (2016). A European aerosol phenomenology-
974	5: Climatology of black carbon optical properties at 9 regional background
975	sites across Europe. Atmos. Environ., 145, 1352-2310. doi: 10.1016/
976	j.atmosenv.2016.09.035
977	Zhao, M., Golaz, JC., Held, I. M., Guo, H., Balaji, V., Benson, R., Xiang, B.
978	(2018). The GFDL Global Atmosphere and Land Model AM4.0/LM4.0: 1.
979	Simulation Characteristics With Prescribed SSTs. Journal of Advances in
980	Modeling Earth Systems 10(3), 691-734. doi: 10.1002/2017MS001208