Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-980, 2016
Manuscript under review for journal Atmos. Chem. Phys.
Published: 15 December 2016

Atmospheric Chemistry and Physics Discussions

Technical note: Fu-Liou-Gu and Corti-Peter model performance evaluation for radiative retrievals from cirrus clouds

Simone Lolli[1], James R. Campbell[2], Jasper R. Lewis[1], Yu Gu[3], Ellsworth J. Welton[4]

[1]NASA GSFC-JCET, Code 612, 20771 Greenbelt, MD, USA

[2] Naval Research Laboratory, Monterey, CA, USA

[3] UCLA, Los Angeles, CA, USA

[4] NASA GSFC, Code 612, 20771 Greenbelt, MD, USA

Corresponding author: simone.lolli@nasa.gov

Abstract

We compare, for the first time, the performance of a simplified radiative transfer algorithm code, the Corti-Peter model, versus the more complex Fu-Liou-Gu model, for resolving top-of-the-atmosphere radiative forcing characteristics from single layer cirrus clouds obtained from the NASA Micro Pulse Lidar Network database in 2010 and 2011 at Singapore. The results of the intercomparison show that differences in annual net TOA cloud radiative forcing can reach 68%. The simplified Corti and Peter, 2009 model proves useful for first-order estimates of TOA cirrus cloud forcing, but may not be suitable for a quantitative estimation, including the sign of cirrus cloud TOA forcing that can readily oscillate around zero globally.

Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-980, 2016
Manuscript under review for journal Atmos. Chem. Phys.
Published: 15 December 2016

1. Introduction

Cirrus clouds play a fundamental role in atmospheric radiation balance and their net radiative effect remains unclear (IPCC 2013; Berry and Mace 2014; Campbell et al. 2016; Lolli et al. 2016a). Feedbacks between cirrus dynamic, microphysical and radiative processes are poorly understood, with ramifications across a host of modeling interests and temporal/spatial scales (Liou 1985; Khvorostyanov and Sassen 1998). Simply put, different models parameterize ice formation in varied, yet relatively simplified, ways that impact how cirrus are resolved, and how their macro/microphysical and radiative properties are coupled with other atmospheric processes (e.g., Comstock et al. 2001; Immler et al. 2008). Consequently, models are very sensitive to small changes in cirrus parameterization (Soden and Donner 1994; Min et al. 2010; Dionisi et al., 2013).

Cirrus clouds are the only tropospheric cloud genus that either exert a positive or negative cloud radiative forcing effect (CRE) during daytime. All other clouds exert a negative daytime top-of-the-atmosphere (TOA) CRE. Cirrus clouds exerting negative net TOA CRE cool the earth-atmosphere system and surface below them. This occurs as the solar albedo term is greater than the infrared absorption and re-emission term. Positive forcing occurs when the two are reversed and infrared warming and re-emission exceed scattering back to space. In contrast, all clouds cause a positive nighttime TOA value, with an infrared term alone and no compensating solar albedo term. This dual property is what makes cirrus distinct, and why it's crucial to understand how well radiative transfer models are resolving TOA CRE properties.

The burgeoning satellite and ground-based era of atmospheric monitoring (Sassen and Campbell 2001; Campbell et al. 2002; Welton et al. 2002; Nazaryan, et al. 2008; Sassen et al. 2008) has led to a wealth of new data for looking at global cirrus cloud properties. In particular, TOA CRE, or at the surface (SFC), are evaluated by means of radiative transfer modeling, designed with different degrees of complexity. What is not yet known is how the relative simplicity of some models translates to a relative retrieval uncertainty, given that the CRE effect of cirrus clouds, at both the ground and TOA, are typically on the order of 1 W m^2. (e.g., Campbell et al. 2016; Lolli et al. 2016a). Whereas some studies show the relative uncertainty of such models as static percentages (Corti and Peter, 2009), the absolute magnitude of uncertainty with respect to cirrus CRE is necessary to understand whether or not they fit within acceptable tolerance thresholds sufficient for quantitative use. Further, given the sensitivity in the sign of net annual cirrus cloud TOA CRE specifically (Campbell et al. 2016), it's plausible that some simpler models are routinely aliasing positive versus negative TOA CRE.

Corti and Peter (2009; CP) describe a simplified radiative transfer model that relies upon a constrained number of input parameters, including surface temperature, cloud top temperature, surface albedo, layer cloud optical depth, and the solar zenith angle. CP simplifies drastically the framework of the Fu-Liou-Gu radiative transfer model (Fu and Liou 1992; Gu et al. 2003; Gu et al., 2011; FLG), for instance, through a parameterization of the longwave and shortwave fluxes derived from the FLG model calculations for realistic atmospheric conditions. Moreover, CP doesn't directly consider gaseous absorption. The model has increasingly been used

Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-980, 2016
Manuscript under review for journal Atmos. Chem. Phys.
Published: 15 December 2016

to assess cirrus cloud radiative effects (Kothe et al. 2011; Kienast-Sjögren et al. 2016; Burgeois et al. 2016) from lidar measurements, owing to its relative simplicity and lower computational burden compared with a model like FLG.

To date, CP model performance vs. FLG model has been evaluated for sensitivities only to simulated synthetic clouds and never on real cases, especially those collected over long periods (Corti and Peter 2009). This can readily be conducted using the unique NASA Micro Pulse Lidar Network (MPLNET; Welton et al. 2002; Campbell et al. 2002; Lolli et al. 2013; Lolli et al., 2014), featuring instruments capable of continuously monitoring cloud optical characteristics. The objective of this technical note is to then assess the absolute differences between CP and FLG in terms of net annual TOA CRE. CP and FLG model performance are evaluated using MPLNET datasets collected from Singapore, a permanent MPLNET observational site, from 2010 and 2011. Our goal is to more appropriately characterize the sensitivities of CP relative to what is generally considered a more complex, and presumably accurate, model, with the hopes of better understanding relative uncertainties, and thus interpreting whether such uncertainties are appropriate for long-term global cirrus cloud analysis.

2. Method

FLG is a combination of the delta four-stream approximation for solar flux calculations (Liou et al. 1988) and a delta-two–four-stream approximation for IR flux calculations (Fu et al. 1997), divided into 6 and 12 bands, respectively. It has been extensively used to assess net cirrus cloud daytime radiative effects, most recently for daytime TOA forcing characteristics within NASA Micro Pulse Lidar datasets (Campbell et al. 2016; Lolli et al. 2016a). The results from these studies have led to the hypothesis of a meridional gradient in cirrus cloud daytime TOA radiative forcing exisiting, with daytime cirrus clouds producing a positive TOA CRE at lower latitudes that reverses to a net negative TOA CRE approaching the non-snow and ice-covered polar regions. They estimate an absolute net cirrus daytime TOA forcing term between 0.03 and 0.27 W m^{-2} over land at a mid-latitude site, which ranges annually between 2.198 - 2.592 W m^{-2} at Singapore. The key here to this phenomenon is the possible oscillation of the net TOA CRE term about zero, which is believed to vary by a maximum +/- 3 W m^{-2} in absolute terms (i.e. normalized for relative cirrus cloud occurrence rate locally) after accounting for polar clouds that should be net cooling elements. Resolving such processes thus requires relatively high accuracy in radiative transfer simulations.

To calculate daytime cirrus cloud radiative effects from MPLNET datasets, the lidar-retrieved single layer cirrus cloud extinction profile (Campbell et al. 2016; Lewis et al., 2016, Lolli et al., 2016a) is transformed into crystal size diameter (using the atmospheric temperature profile) and ice water content (*IWC*) profiles using the parameterization proposed by Heymsfield et al. (2014). Those parameters, at each range bin, are input into FLG model. The thermodynamic atmospheric profiles, together with ozone concentrations are obtained with a temporal resolution of +/- 3 hr, from a meteorological reanalysis of the NASA Goddard Earth Observing System Model Version 5.9.12 (GEOS-5). In contrast, for a given cloud case, the corresponding cloud and atmospheric CP input parameters would explicitly be the surface temperature, the cloud top temperature, the surface albedo, the cloud optical depth for the specific layer and the solar zenith angle.

Calculations here are performed for two different values of the surface albedo, which is a common input parameter in both models. These values are fixed at 0.12 and 0.05, respectively, as Singapore is a metropolitan area completely surrounded by sea. This allows us to more reasonably characterize forcing over the broader archipelago of Southeast Asia, and follows the experiments described by Lolli et al. (2016b; in review). Here we reconsider these results by intercomparing those solved with FLG and CP for net daytime TOA CRE over a practical range of cloud optical depth (COD). As described in both Campbell et al. 2016 and Lolli et al. 2016a, daytime is specifically defined in these experiments as those hours where incoming net solar energy exceeds that outgoing. Only under such circumstances can the net TOA CRE term become negative. Otherwise, it is effectively nighttime, as the term is positive and all clouds induce a warming TOA term.

3. Intercomparisons

The yearly daytime cirrus net TOA CRE, normalized by corresponding occurrence frequency versus COD, is evaluated at Singapore (1.3 N, 103.8 E, 20 m above sea level) for the FLG and CP models. The method to estimate cirrus clouds optical properties is described in Lewis et al. 2015 and Campbell et al. 2016, for both 20 and 30sr solutions from the unconstrained single-wavelength elastic lidar equation (Campbell et al. 2016). For both models, the daytime cirrus cloud net TOA CRE is calculated as the difference of two computations using different assumed states (cloudy sky minus cloud and aerosol particulate-free conditions) to isolate the distinct cirrus impact alone (in W m^{-2}).

3.1 Singapore 2010

FLG and CP were compared over a total of 15039 daytime single layer cirrus clouds. Detailed consideration of how this cloud sample is resolved in Level 2 MPLNET datasets can be found in Lewis et al. (2016) and Campbell et al. (2016). Figures 1, 2, 3 and 4 show histograms of cirrus cloud relative frequency and net annual daytime TOA CRE normalized by corresponding frequency at Singapore in 2010, for both surface albedo values of 0.05 (Fig. 3 and 4; i.e., over sea) and 0.12 (Fig. 1 and 2; i.e. over land) at 0.03 COD resolution from 0 to 3, chosen consistent with Sassen and Cho (1992). Note, since a common cloud sample is used, the 20 sr samples vary in COD between 0 and approximately 1.

Intercomparison of TOA CRE vs. COD over the ocean at 20sr shows an overall forcing of 1.73 W m^{-2} for CP and 0.54 W m^{-2} for FLG. At 30sr, we obtain -0.17 W m^{-2} from CP and -0.10 W m^{-2} for FLG. The overall CP CRE is greater in absolute magnitude than FLG by up to a maximum difference of 68%. This value is obtained by taking the ratio between yearly CRE from FLG over CP and then the percentage difference. Over land (urban environment), CP yearly TOA CRE are higher than the FLG model by 41% (CP = 4.85 W m2, FLG=2.85 W m^{-2} at 20sr; CP=5.21 W m^{-2} and FLG=2.36 W m^{-2} at 30sr). The COD value at which cirrus begin cooling the earth-atmosphere system, moving toward higher COD, is systematically shifted towards higher values for CP with respect to FLG. This is particularly evident over ocean at 20sr where there is a shift of 0.2 in COD (0.6 for CP and 0.4 for FLG; Figure 3).

3.2 *Singapore 2011*

The same analysis was performed for the 2011 dataset, but during this year the two models were intercompared over 18033 detected daytime cloud profiles. Over ocean, CRE vs. COD results show a total net TOA CRE of 1.01 W m^{-2} for CP and 0.57 W m^{-2} for FLG at 20sr, while at 30sr the forcing is negative: -1.52 W m^{-2} for CP and -0.52 W m^{-2}. The discrepancies in absolute magnutde are thus near 65%. Over land, differences drop to 21% (CP = 3.90 W m^{-2}, FLG=3.07 W m^{-2} at 20sr; CP=3.77 W m^{-2} and FLG=3.32 W m^{-2} at 30%). Again it can be seen that there is a shift in COD turning point value (0.65 COD for CP and 0.35 for FLG at 20sr; Figure 3).

To better understand the different outputs between the two radiative transfer models, a scatter plot between from FLG barplot entries in Fig. 2 and 4 (30sr solution) and the corresponding CP barplot values has been plotted for each year, over land and over ocean (Fig. 5 and 6). The red line represents the actual data linear regression while the blue line it is the ideal case (slope=1, intercept=0). It can be noticed that the slope coefficient from regression it is insensitive to the year and to the different type of surface (values range from 1.4 to 1.6). The CP model, however, is on average magnifying 1.5 times the FLG radiative forcing. On the contrary, for that concerns the bias (or the intercept from the linear regression) it is interesting to highlight that this term is sensitive to the year and to the type of surface underlying the cirrus cloud (land/ocean). For very thin cirrus clouds there is a switch in sign (from cooling to

Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-980, 2016
Manuscript under review for journal Atmos. Chem. Phys.
Published: 15 December 2016

warming or vice-versa between the two models) between the two models, i. e. thin cirrus clouds over land in 2011 with a positive FLG CRE in the interval 0-0.93 W m^{-2} will be coolers for CP. The substantial differences between the two models may be ascribed to the CP model simplifications in terms of cloud emissivity that depends only on COD and/or the neglected longwave absorption above the cloud.

4. Conclusions

Annual single-layer cirrus cloud top-of-the-atmosphere (TOA) radiative effects (CRE) calculated from the Corti and Peter (2009) radiative transfer model (CP) are compared with similar results from the more complex, and presumably more accurate, Fu-Liou-Gu (FLG) radiative transfer model. The CP model calculates CRE using a parameterization of longwave and shortwave fluxes that are derived from real measurements. Overall, CP uses less input parameters compared with FLG, making it practically and computationally more efficient. This is the first time, though, that the two models are compared using long-term datasets, as opposed to synthetic datasets, with experiments conducted using NASA Micro Pule Lidar datasets collected at Singapore in 2010 and 2011, following experiments first described by Lolli et al. (2016; in review).

The net TOA CRE was evaluated versus cloud optical depth (COD) for steps of 0.03 (COD range: 0-1) at 20sr and for steps of 0.1 at 30sr (COD range: 0-3). Our findings suggest that the difference in annual net TOA CRE between the two models is higher than the 20% value reported in Corti and Peter (2009), approaching 68% in in one annual net TOA CRE experiment. Our results show that the CP TOA CRE yearly

Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-980, 2016
Manuscript under review for journal Atmos. Chem. Phys.
Published: 15 December 2016

values are always larger in absolute magnitude than those calculated with FLG model. The smaller difference between the two models in yearly TOA CRE estimations is over land in general (largest difference 41%). We speculate that these differences are driven by specific simplifications in CP relative to FLG. In particular, cloud emissivity depending only on COD and no longwave absorption being considered above clouds.

In spite of this comparison, even if we can speculate that FLG model is more accurate overall, because of its relative complexity compared with CP, we are still missing regular comparisons of FLG with real observational data. Thus, the practical gains to long-term application of a simplified model like CP cannot be overstated, given lower computational demands. However, we think that the results from this study are noteworthy because they show that the differences between the two models are significant. With respect to cirrus annual net TOA CRE, and given the perspective on their global distribution described by Campbell et al. (2016) and Lolli et al. (2016; in review), these sensitivities can lead to completely different conclusions about global cirrus TOA forcing effects. Therefore, in future work, it is imperative on the community to continue understanding and refining the global parameterizations used in all radiative transfer models regarding cirrus. Continued intercomparisons between models with real observation both at ground (using flux measurements), in situ (aircraft measurements) and at TOA (using satellite-based measurements,) remain critical interests. Further, dividing shortwave and longwave bands to investigate whether or not there are wavelength selective differences in CRE estimations between specific bands than currently recognized can improve our analysis.

Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-980, 2016
Manuscript under review for journal Atmos. Chem. Phys.
Published: 15 December 2016

Acknowledgements

This study and the NASA Micro Pulse Lidar Network (MPLNET) are supported by the NASA Radiation Sciences Program (H. Maring). Author JRC acknowledges the Naval Research Laboratory Base Program and support of NASA Interagency Agreement NNG15JA17P on behalf of MPLNET.

Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-980, 2016
Manuscript under review for journal Atmos. Chem. Phys.
Published: 15 December 2016

References

Berry, E., and G. G. Mace, 2014: Cloud properties and radiative effects of the Asian summer monsoon derived from A-Train data. J. Geophys. Res. Atmos., 119, doi:10.1002/2014JD021458.

Campbell, S. Lolli J. Lewis, Y. Gu, E. Welton, 2016 "Daytime Cirrus Cloud Top-of-Atmosphere Radiative Forcing Properties at a Midlatitude Site and their Global Consequence" *J. Applied Meteor. Climat*, http://dx.doi.org/10.1175/JAMC-D-15-0217.1

Campbell, et al., 2002," "Aerosol Lidar Observation at Atmospheric Radiation Measurement Program Sites: Instrument and Data Processing", J*. Atmos. Oceanic Technol.*, 19, 431-442

Comstock, J.M., T.P. Ackerson (2001), G. G. Mace:,"Cirrus radiative properties in the tropical western pacific. *Eleventh ARM Science Team Meeting Proceedings*, Atlanta, Georgia, March 19-23.

Corti, T. and Peter, T., 2009: "A simple model for cloud radiative forcing", *Atmos. Chem. Phys.*, 9, 5751-5758, doi:10.5194/acp-9-5751-2009

Dionisi, D., Keckhut, P., Liberti, G. L., Cardillo, F., and Congeduti, F., 2013: Midlatitude cirrus classification at Rome Tor Vergata through a multichannel Raman–Mie–Rayleigh lidar, Atmos. Chem. Phys., 13, 11853-11868, doi:10.5194/acp-13-11853-2013.

Fu, Q., K. N. Liou, 1992, "On the correlated *k*-distribution method for radiative transfer in nonhomogeneous atmospheres", *J. Atmos. Sci.*, 49, 2139–2156, 1992.

Gu, Y., J. Farrara, K. N. Liou, and C. R. Mechoso, 2003: Parameterization of cloud-radiation processes in the UCLA general circulation model. *J. Climate*, 16, 3357-3370.

Gu, Y., K. N. Liou, S. C. Ou, and R. Fovell, 2011: Cirrus cloud simulations using WRF with improved radiation parameterization and increased vertical resolution. *J. Geophys. Res*. 116, D06119, doi:10.1029/2010JD014574

Heymsfield, A., D. Winker, M. Avery, M. Vaughan, G. Diskin, M. Deng, V. Mitev, and R. Matthey, 2014: Relationships between ice water content and volume extinction coefficient from in situ observations for temperatures from 0° to −86°C: Implications for spaceborne lidar retrievals. *J. Appl. Meteor. Climatol.*, 53, 479–505

Immler, F., Treffeisen, R., Engelbart, D., Krüger, K., and Schrems, O. 2008: "Cirrus, contrails, and ice supersaturated regions in high pressure systems at northern mid latitudes", *Atmos. Chem. Phys.*, 8, 1689-1699, doi:10.5194/acp-8-1689-2008.

IPCC: Climate Change 2013 – The Physical Science Basis, Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Inter- governmental Panel on Climate Change, Cambridge University Press, Cambridge, UK and New York, NY, USA, 2014.

Khvorostyanov V. I. and K. Sassen, 1998: Cirrus Cloud Simulation Using Explicit Microphysics and Radiation. Part I: Model Description. J. Atmos. Sci., 55, 1808–1821

Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-980, 2016
Manuscript under review for journal Atmos. Chem. Phys.
Published: 15 December 2016

Kienast-Sjögren, E., Rolf, C., Seifert, P., Krieger, U. K., Luo, B. P., Krämer, M., and Peter, T.: Climatological and radiative properties of midlatitude cirrus clouds derived by automatic evaluation of lidar measurements, Atmos. Chem. Phys., 16, 7605-7621, doi:10.5194/acp-16-7605-2016, 2016.

Kothe, S., Dobler, A., Beck, A. and Ahrens, B., 2011. The radiation budget in a regional climate model. *Climate dynamics*, *36*(5-6), pp.1023-1036.

Kuo-Nan Liou, 1986: Influence of Cirrus Clouds on Weather and Climate Processes: A Global Perspective. Mon. Wea. Rev., 114, 1167–1199,

Lolli S., J. Lewis, R. Campbell, Y. Gu, E. Welton, 2016a, "Cirrus Cloud Radiative Characteristics from Continuous MPLNET Profiling at GSFC in 2012", *Óptica pura y aplicada,* Vol. 49 (1), 1-6,doi:10.7149/OPA.49.1.1.

Lolli et al., 2016b, "Daytime Top-of-the-Atmosphere Cirrus Cloud Radiative Forcing Properties at Singapore", *Submitted to Journal of Applied Climatology and Meteorology*, 27 July 2016.

Lolli S. et al, 2013a, "Evaluating light rain drop size estimates from multiwavelength micropulse lidar network profiling.,"*J. Atmos. Oceanic Technol.*, **30**, 2798–2807.

Lolli S. et al. 2014. "High Spectral Resolution Lidar and MPLNET Micro Pulse Lidar aerosol optical property retrieval intercomparison during the 2012 7-SEAS field campaign at Singapore." *Proc. SPIE 9246, Lidar Technologies, Techniques, and Measurements for Atmospheric Remote Sensing X*, 92460C (October 20, 2014); doi:10.1117/12.2067812.

Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-980, 2016
Manuscript under review for journal Atmos. Chem. Phys.
Published: 15 December 2016

Lewis, J. R., J. R. Campbell, P. C. Haftings and E. J. Welton, 2015: Overview and analysis of the MPLNET Version 3 cloud detection algorithm. *J. Atmos. Oceanic Technol.,* submitted

Min, M., P. Wang, J. R. Campbell, X. Zong, and Y. Li, 2010, "Midlatitude cirrus cloud radiative forcing over China", J. Geophys. Res., 115, D20210, doi:10.1029/2010JD014161.

Nazaryan, H., M. P. McCormick, and W. P. Menzel, 2008, "Global characterization of cirrus clouds using CALIPSO data", J. Geophys. Res., 113, D16211, doi:10.1029/2007JD009481.

Sassen, K. and J. R. Campbell, 2001: A Midlatitude Cirrus Cloud Climatology from the Facility for Atmospheric Remote Sensing. Part I: Macrophysical and Synoptic Properties. J. Atmos. Sci., 58, 481–496,

Sassen, K., Z. Wang, and D. Liu, 2008, "Global distribution of cirrus clouds from CloudSat/Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) measurements", J. Geophys. Res., 113, D00A12, doi:10.1029/2008JD009972.

Soden, B. J., and L. J. Donner (1994), Evaluation of a GCM cirrus parameterization using satellite observations, J. Geophys. Res., 99(D7), 14401–14413, doi:10.1029/94JD00963.

Welton, E. J., et al., 2002: Measurements of aerosol vertical profiles and optical properties during INDOEX 1999 using micropulse lidars. *J. Geophys. Res.*, 107, 8019,

Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-980, 2016
Manuscript under review for journal Atmos. Chem. Phys.
Published: 15 December 2016

FIGURES

FIGURE 1 Analysis over land (Albedo=0.12) for 20sr solution. Top Panel: CRE vs. COD weighted by occurrence frequency for Corti and Peter(red) and FLG (blue) models on 2011. Bottom Panel: CRE vs. COD weighted by occurrence frequency for Corti and Peter(red) and FLG (blue) models on 2010

FIGURE 2 Analysis over land (Albedo=0.12) for 30sr solution. Top Panel: CRE vs. COD weighted by occurrence frequency for Corti and Peter(red) and FLG (blue) models on 2011. Bottom Panel: CRE vs. COD weighted by occurrence frequency for Corti and Peter(red) and FLG (blue) models on 2010

FIGURE 3 Same as Figure 1, but over the ocean (Albedo=0.05)

FIGURE 4 Same as Figure 2, but over the ocean (Albedo=0.05)

FIGURE 5 Scatter plot and linear regression for 30sr solution for FLG and CP CRE in 2010 over land (upper panel) and ocean (lower panel)

FIGURE 6 Scatter plot and linear regression for 30sr solution for FLG and CP CRE in 2011 over land (upper panel) and ocean (lower panel)

Tables

CRE vs. COD	Land	Ocean
2010	20sr CP=4.85 FLG=2.85 (41%)	20sr CP=1.73 FLG=0.54 (68%)
	30sr CP=5.21 FLG=3.36 (35%)	30sr CP=-0.17FLG=-0.09 (40%)
2011	20sr CP=3.90 FLG=3.07 (21%)	20sr CP=1.01 FLG=0.43 (57%)
	30sr CP=3.77 FLG=3.32 (12%)	30sr CP=-1.52 FLG=-0.52 (65%)

Table 1 Summary of principal differences between FLG and CP radiative transfer model depending on year and on land/ocean.

Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-980, 2016
Manuscript under review for journal Atmos. Chem. Phys.
Published: 15 December 2016

Atmospheric Chemistry and Physics
Open Access
Discussions

Figures

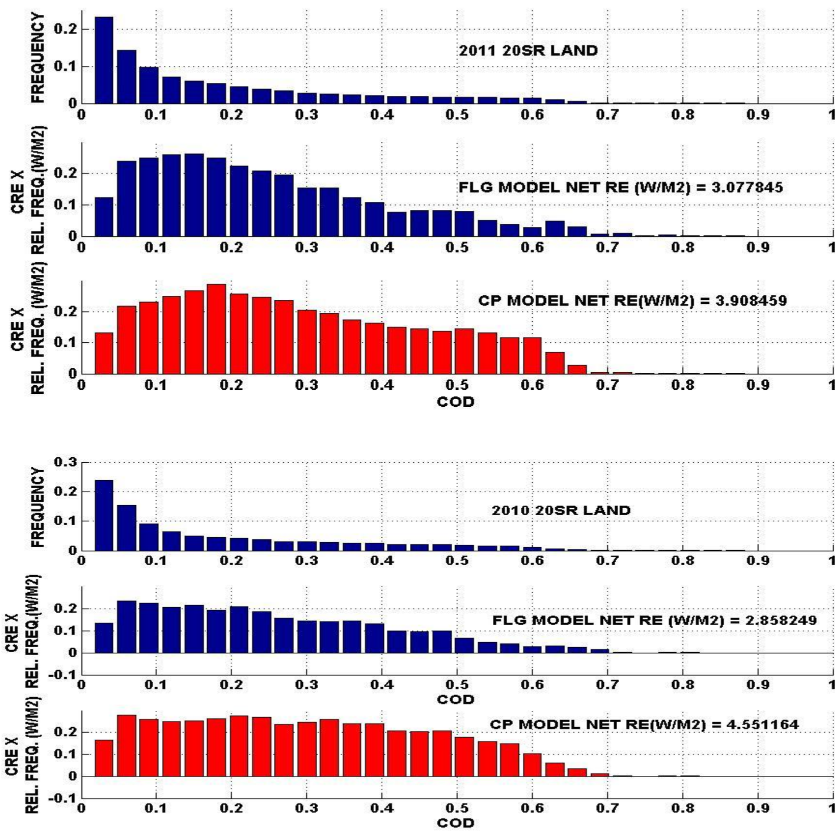


Figure 1 Analysis over land (Albedo=0.12) for 20sr solution. Top Panel: CRE vs. COD weighted by occurrence frequency for Corti and Peter(red) and FLG (blue) models on 2011. Bottom Panel: CRE vs. COD weighted by occurrence frequency for Corti and Peter(red) and FLG (blue) models on 2010

Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-980, 2016
Manuscript under review for journal Atmos. Chem. Phys.
Published: 15 December 2016

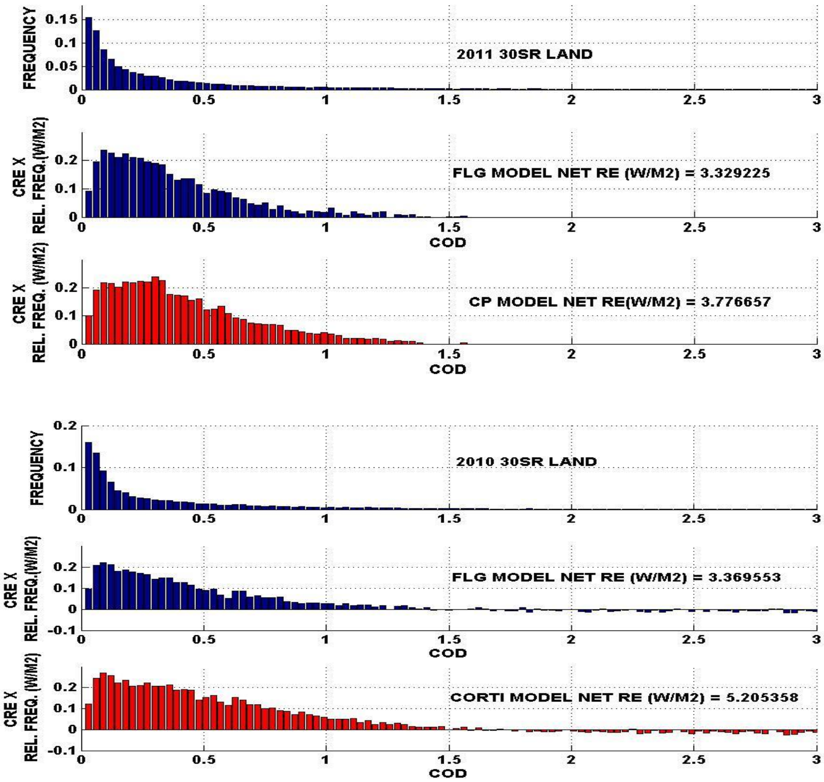


Figure 2 Analysis over land (Albedo=0.12) for 30sr solution. Top Panel: CRE vs. COD weighted by occurrence frequency for Corti and Peter(red) and FLG (blue) models on 2011. Bottom Panel: CRE vs. COD weighted by occurrence frequency for Corti and Peter(red) and FLG (blue) models on 2010

Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-980, 2016
Manuscript under review for journal Atmos. Chem. Phys.
Published: 15 December 2016

Atmospheric Chemistry and Physics
Discussions
Open Access

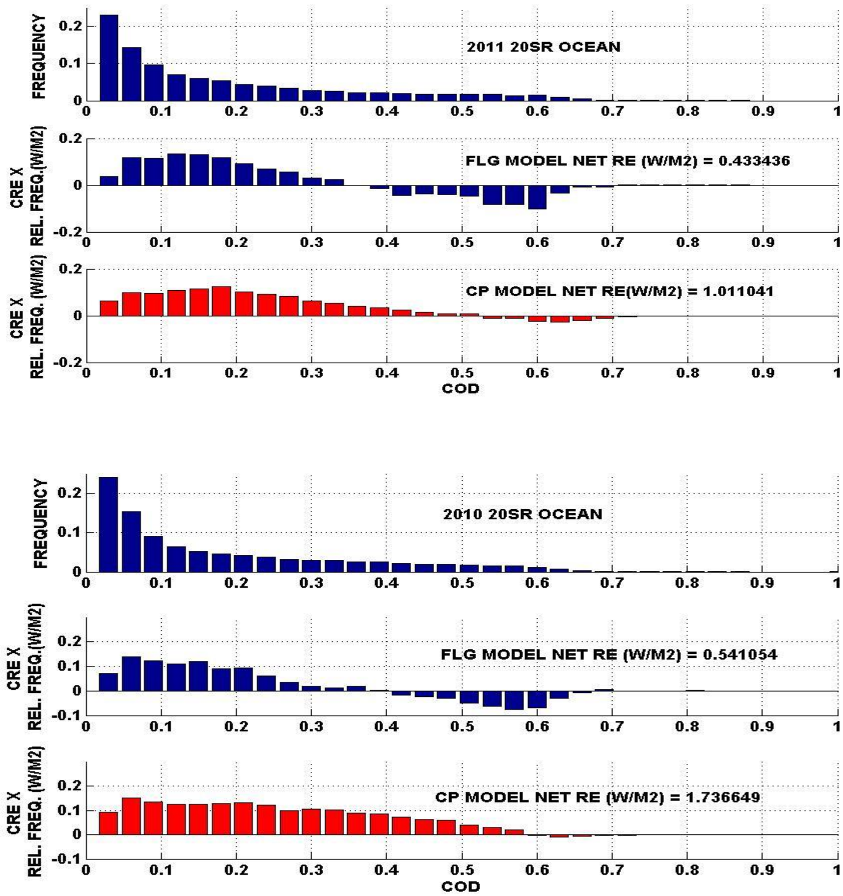


Figure 3 Same as Figure 1, but over the ocean (Albedo=0.05)

Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-980, 2016
Manuscript under review for journal Atmos. Chem. Phys.
Published: 15 December 2016

Atmospheric Chemistry and Physics
Discussions
Open Access

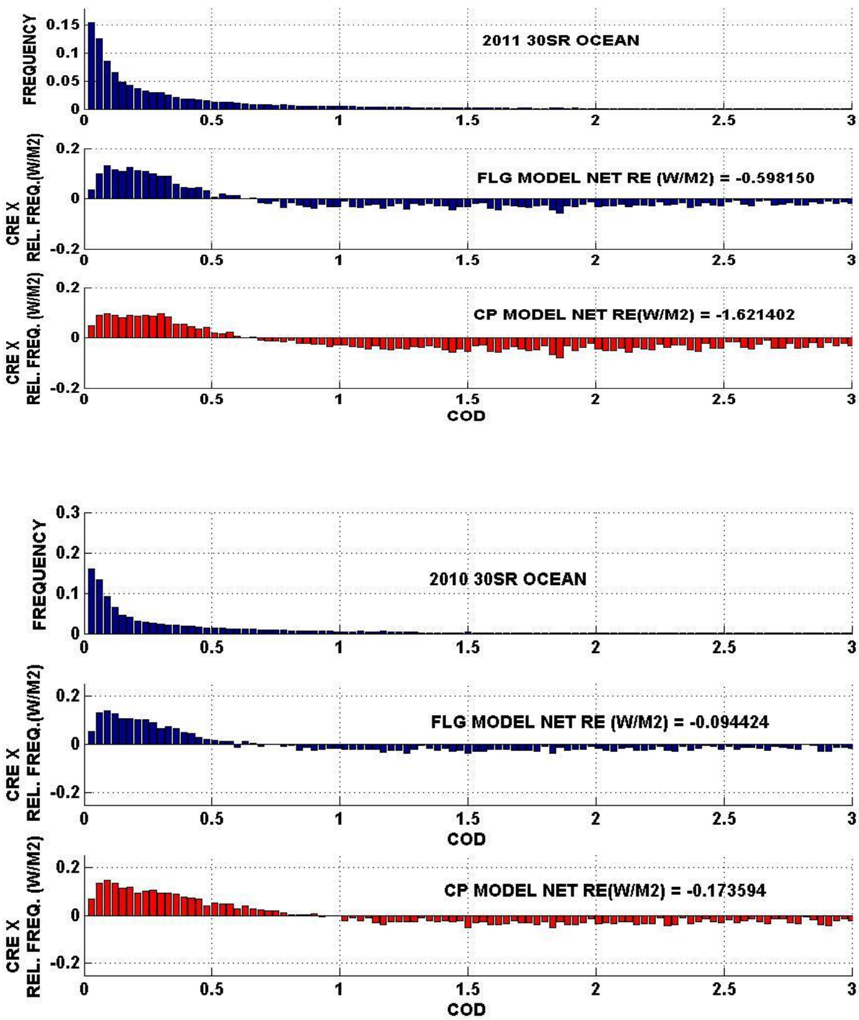
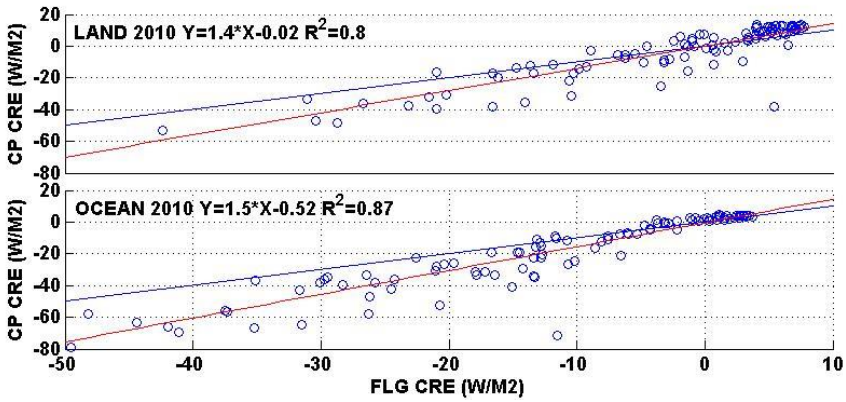


Figure 4 Same as Figure 2, but over the ocean (Albedo=0.05)

Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-980, 2016
Manuscript under review for journal Atmos. Chem. Phys.
Published: 15 December 2016

Atmospheric Chemistry and Physics
Discussions
Open Access



372 **Figure 5** Scatter plot and linear regression for 30sr solution for FLG and CP CRE in 2010 over land
373 (upper panel) and ocean (lower panel)
374

Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-980, 2016
Manuscript under review for journal Atmos. Chem. Phys.
Published: 15 December 2016

Atmospheric Chemistry and Physics Discussions
Open Access

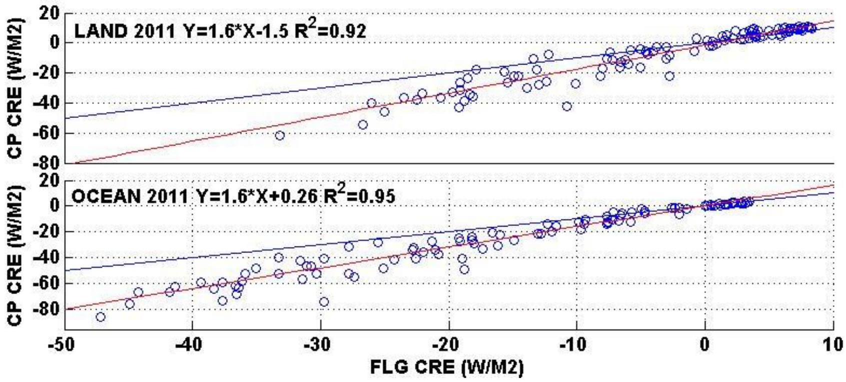


Figure 6 Scatter plot and linear regression for 30sr solution for FLG and CP CRE in 2011 over land (upper panel) and ocean (lower panel)