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

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Abstract

We compare, for the first time, the performance of a simplified atmospheric radiative transfer algorithm package, the Corti-Peter (CP) model, versus the more complex Fu-Liou-Gu (FLG) 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. Specifically, CP simplifies calculation of clear-sky longwave radiation through regression analysis, which contributes significantly to differences between the two. The results of the intercomparison show that differences in annual net TOA cloud radiative forcing can reach 68%. CP proves useful for first-order estimates of TOA cirrus cloud forcing, but may not be suitable for quantitative accuracy, including the absolute sign of cirrus cloud TOA forcing that can readily oscillate around zero globally.

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. 2017). 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 exerts a positive or negative top-of-the-atmosphere (TOA) cloud radiative forcing effect (CRE) during daytime. All other clouds exert a negative daytime 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. 2017). 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 does not directly consider gaseous absorption. The model has increasingly been used 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 measurements, especially those collected over long periods (Corti and Peter 2009). Such evaluation, however, 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 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 in 2010 and 2011, a permanent tropical MPLNET observational site, and Greenbelt, Maryland in 2012, a midlatitude site. Our goal is to more appropriately characterize the sensitivities of CP relative to what is generally considered a more complex, and presumably more 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 MPLNET datasets (Campbell et al. 2016; Lolli et al. 2017). The results from these studies have led to the hypothesis of a meridional gradient in cirrus cloud daytime TOA radiative forcing existing, with daytime cirrus clouds producing a positive daytime TOA CRE at lower latitudes that reverses to a net negative daytime 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 and varying surface albedos over land and water exclusively (i.e., not ice). 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., 2017) 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. 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 are explicitly 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 MPLNET observational sites, Singapore and Greenbelt, Maryland (i.e., NASA Goddard Space Flight Center; GSFC). For the former site, two different values of the surface albedo, which is a common input parameter in both models, 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. (2017). . At NASA GSFC, only a single over-land albedo is used, though one that varies monthly between 0.12-0.15 based on climatology. Here we reconsider these results by first 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. (2017), 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. Nighttime results will considered as context to understanding net diurnal differences between the models when examining the GSFC dataset.

3. Intercomparisons

The yearly daytime cirrus net TOA CRE, normalized by corresponding occurrence frequency, in this case as a function of COD, was evaluated at Singapore (1.3 N, 103.8 E, 20 m above mean sea level) and GSFC (38.9 N, 76.8 W, 39m above mean sea level) for both FLG and CP. The method to estimate MPLNET cirrus clouds optical properties is described in Lewis et al. (2015) and Campbell et al. (2016), for both 20 and 30 sr 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 model computations using different assumed states (cloudy sky minus cloud and aerosol particulate-free conditions) to isolate the distinct cirrus cloud impact alone (in W m^{-2}).

3.1 Model sensitivities

An initial sensitivity study was carried out to evaluate how the input parameters, and eventually their uncertainties, influence the net TOA CRE calculations. Results are summarized in Table 1. Model input parameter sensitivities were investigated for surface albedo, COD, earth surface temperature and cloud top temperature. Table 1 shows how much the CRE changes by varying each individual parameter alone. For instance, changing the surface albedo from 0.12 to 0.14 and keeping the other three parameters fixed produces a change of 22% for CP model and 24% for FLG model. Changing COD from 1 to 1.1 produces a change in CRE of 14% for CP and 18% for FLG. Changing surface temperature and cloud top temperature of 1 K produces respective changes of 11% and 6% for CP and 7% and 5% for FLG. Though subtle, the models exhibit some differences in variance relative to the input parameters required to initialize them.

3.2 Singapore 2010

FLG and CP were compared over a total of 15039 daytime single layer cirrus clouds at Singapore in 2010. Detailed consideration of how such a 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 reflect histograms of cirrus cloud relative frequency and net annual daytime TOA CRE normalized by corresponding frequency, 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. This latter range was chosen as consistent with Sassen and Cho (1992), and the nominal effective COD range corresponding with cirrus cloud occurrence. Note, since a common cloud sample is used, the 20 sr samples vary in COD between only 0 and approximately 1 in contrast to the 30 sr sample topping out at 3.

Intercomparison of net daytime TOA CRE vs. COD over the ocean at 20 sr shows an overall forcing of 1.73 W m^{-2} for CP and 0.54 W m^{-2} for FLG. At 30 sr, we obtain -0.17 W m^{-2} from CP and -0.10 W m^{-2} for FLG. The overall CP net TOA CRE is greater in absolute magnitude than FLG by 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 net daytime TOA CRE are higher than the FLG model by 41% (CP = 4.85 W m2, FLG=2.85 W m^{-2} at 20 sr; CP=5.21 W m^{-2} and FLG=2.36 W m^{-2} at 30 sr). 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 20 sr where there is a shift of 0.2 in COD (0.6 for CP and 0.4 for FLG; Fig. 3).

3.3 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 daytime TOA CRE of 1.01 W m^{-2} for CP and 0.57 W m^{-2} for FLG at 20 sr, while at 30 sr the forcing is negative: -1.52 W m^{-2} for CP and -0.52 W m^{-2}. The discrepancies in absolute magnitude are thus near 65%. Over land, differences drop to 21% (CP = 3.90 W m^{-2}, FLG = 3.07 W m^{-2} at 20 sr; 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 20 sr; Fig. 3).

To better understand the different outputs between the two models, a scatter plot between from FLG barplot entries is shown in Figs. 2 and 4 (30 sr solution), and the corresponding CP barplot values are plotted for each year, over land and over ocean, in Figs. 5 and 6. The red line represents the actual linear data regression, while the blue line represents an ideal case (i.e., slope=1, intercept=0). If the two radiative transfer models show identical results regarding CRE, all the points should lie on the blue line. The red line instead represents the actual regression line, or a relative measure of how much the two models differ.

From Figs. 5 and 6, the FLG-derived net daytime TOA CRE of 1 W/m^2 corresponds with CP values ranging from 1.4 W/m^2 to 1.6 W/m^2. This implies that CP daytime TOA CRE values are systematically greater in absolute value than the corresponding FLG values by 40%-60%. On the contrary, the bias (or the intercept from the linear regression) shows higher variability depending on the year and surface type underlying the cirrus cloud (land versus ocean). This indicates that when a cirrus cloud shows a neutral effect (0 W/m^2) in FLG solutions radiative CP calculations range from 0.02 to -1.5 W/m^2, again depending on year and surface albedo. This implies that characterization of cirrus cloud warming or cooling effects must carefully be determined with these models.

3.4 Greenbelt, Maryland 2010

To limit potential assessment ambiguity based on a single-site analysis, we performed a second model comparison using the 2010 NASA GSFC dataset. A summary of this dataset and net daytime TOA CRE results can be found in Campbell et al. (2016). As this site in land-locked, only the single albedo was, again, used, though varied monthly based on climatological passive satellite estimates. 21107 daytime cirrus cloud profiles were considered. In Figure 7 is plotted the total net TOA CRE vs. COD at 30 sr, for CP (-2.59 W/m^2) against FLG (0.05 W/m^2). A relative differencing here is impractical. Suffice however, this is a significant difference, and the sign of the net daytime forcing term is in direct question between the two.

With this NASA GSFC dataset, we further consider an additional 32185 nighttime cirrus cloud cases within the analysis (Fig. 7). The thought here is that, relative to prior estimates of CP uncertainty compared with more complex models, a diurnal average would be likely to produce a different, and plausibly closer, relative agreement consistent with prior studies. That is, since during for most of the period we define here as night there is no solar input, a simplification of the infrared forcing terms and parameterizations alone would potentially yield a closer comparison between the two models. For the NASA GSFC dataset, we solved net nighttime TOA CRE of 29.1 W/m^2 with FLG compared with 21.0 W/m^2 with CP, or a relative difference approaching 50%. This is a slightly lower than the Singapore comparison, for example, but still higher than previously stated (Corti and Peter 2009). Table 2 summarizes the discrepancies in terms of CRE at both observational sites.

It is useful at this point to discuss some of the potential elements driving these differences. The larger discrepancies between the two models is likeliest ascribed to the optimization of three specific parameters in the CP model: the first two, σ^* and k^* (Eq. 2 of Corti and Peter, 2009) are respectively the approximated values for the Stefan-Boltzmann constant and the surface temperature exponent obtained from regression analysis and used to calculate the outgoing longwave earth radiation. Instead, the last parameter, γ^* (again obtained from a regression analysis), is related to the asymmetry factor and used to calculate the cloud reflectance of shortwave radiation (Eq. 11 in Corti and Peter; 2009). We speculate that, though the analysis is left to a future study on broader uncertainties in modeling ice radiative properties inherently with any model, these parameters are not the constants ascribed by CP, but that their values instead change with respect to season and latitude.

The 20% relative accuracy claimed in Corti and Peter (2009) may be verified for special conditions in tropical latitudes, where the three parameters discussed above are well optimized. But, that is clearly not found from our study. Corti and Peters (2009) expressly stated that they used fixed values for those three parameters (again σ^* and k^* in Eq. 2 and γ^* in Eq. 11 in Corti e Peter, 2009) again using regression analysis, but this shouldn't be the case, as net TOA CRF is very sensitive to those parameters. For example, varying water vapor concentrations in the atmosphere can be the responsible of a difference up to 25 W/m^2 (for temperatures at the surface higher than 288K) in clear-sky earth longwave radiation at Singapore, as stated in Corti and Peter (2009; Fig. 1). In our analysis we verified that, over one year, the surface temperature is higher than 288K 66% of the time. We advise that those looking to apply CP to long-term climate/cirrus cloud study should carefully analyze the relevance of these settings to their given experiment before directly applying the model.

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 optimized for a tropical environment. Values for theses parameterizations, as suggested in Corti and Peter (2009), lead to relative differences in TOA CRE that far exceed the stated 20% in the original manuscript. This includes parsing results out for daytime, nighttime or diurnal averages. It is believed that these parameterizations cannot be considered global constants, as originally defined for CP, but that they should be carefully evaluated on single case basis for each experiment. Overall, CP uses less input parameters compared with FLG, making it practically and computationally more efficient, particularly for large climate datasets. This is the first time, however, that the two models are compared using long-term cirrus clouds datasets, as opposed to synthetic datasets, with experiments conducted using NASA Micro Pulse Lidar datasets collected at Singapore in 2010 and 2011 (Lolli et al. 2017) and Greenbelt, Maryland in 2012.

More specifically, net daytime TOA CRE was evaluated versus cloud optical depth (COD) for steps of 0.03 (COD range: 0-1) at 20 sr and for steps of 0.1 at 30 sr (COD range: 0-3) for both the Singapore and Greenbelt, Maryland datasets. Our findings suggest that the difference in annual net TOA CRE between the two models approaches 68% in one experiment at Singapore. At Greenbelt, Maryland, the sign of the net annual daytime TOA CRE term differs, and the absolute difference varies between by nearly 2.5 W/m^2. Differences in the sign of the net TOA forcing term, however, is most worrying. Since cirrus clouds are the only cloud that can exhibit daytime positive or negative net TOA CRE, subtle differences in absolute magnitude are less important than whether or not the clouds are inducing a cooling or forcing term in the TOA radiation budget.

In spite of this comparison, even if we reasonably speculate that FLG is the more accurate model 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 believe 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. (2017), 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.

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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)

FIGURE 7 Analysis on 2010 dataset from MPLNET GSFC observational site for 30sr solution daytime (upper panel) and nighttime (lower panel).

Tables

	ALBEDO	COD	T surf	Cloud top T
CP	22%	14%	11%	6%
FLG	24%	18%	7%	5%

Table 1 Sensitivity of CP and FLG radiative transfer model with respect to the surface albedo, cloud optical depth (COD). Unperturbed parameters are COD=1, Surface albedo=0.12, Tsurf=294K Cloud top T=229K. The variation in net radiative forcing expressed in percentage for each parameter are calculated changing the surface albedo from 0.12 to 0.14, the COD from 1 to 1.1, and augmenting the temperatures of 1K.

CRE vs. COD	Land	Ocean
SING 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%)
SING 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%)
GSFC 2010	30sr CP=-2.59 FLG=0.05	

Table 2 Summary of principal CRE (W/m^2) differences between FLG and CP radiative transfer model depending on year and on land/ocean.

Figures

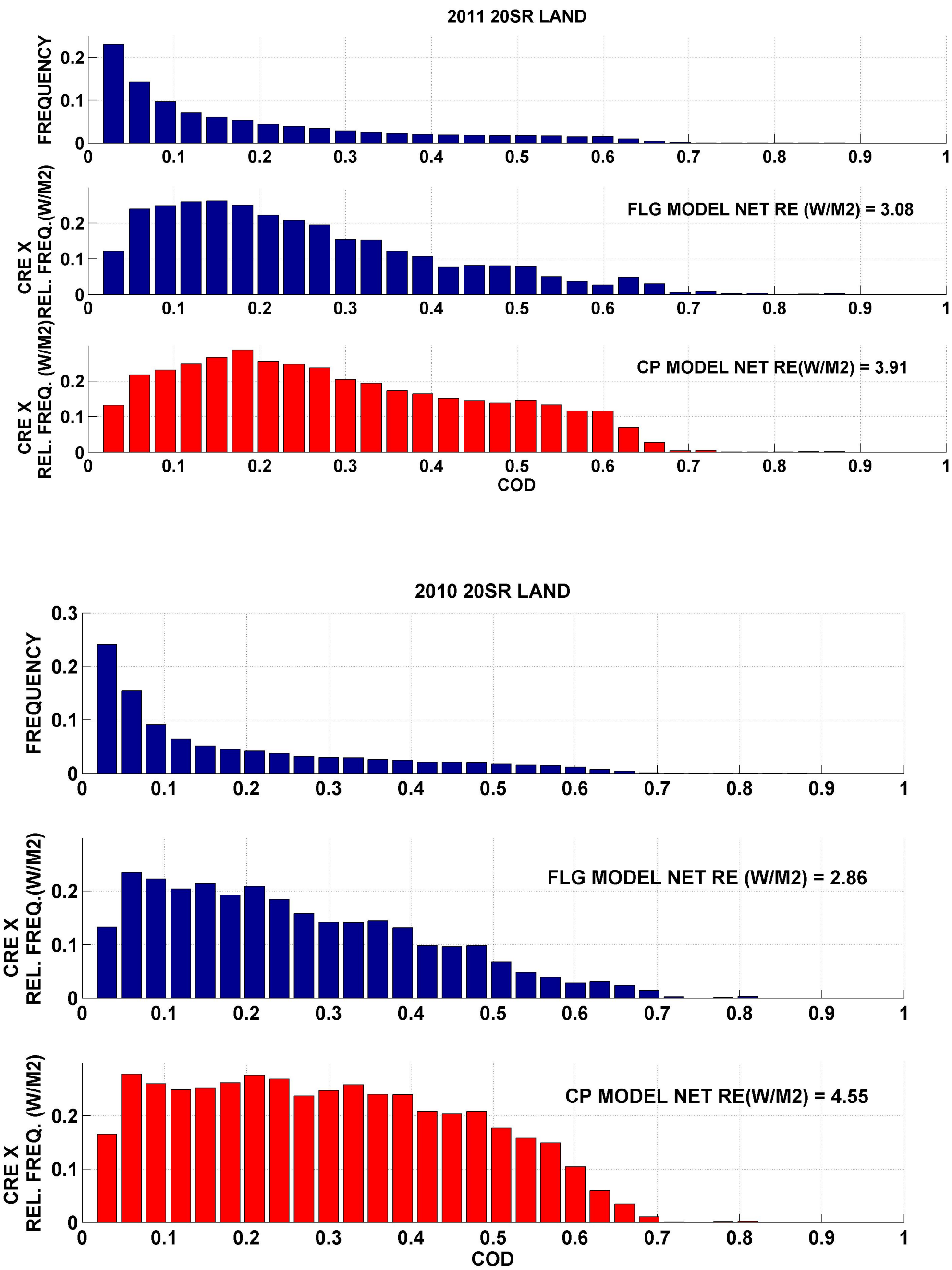


Figure 1 Analysis over land (Albedo=0.12) for 20sr solution. Top Panel: CRE vs. COD weighted by occurrence frequency for Corti and Peter(red) and FLG (blue) models on 2011. Bottom Panel: CRE vs. COD weighted by occurrence frequency for Corti and Peter(red) and FLG (blue) models on 2010

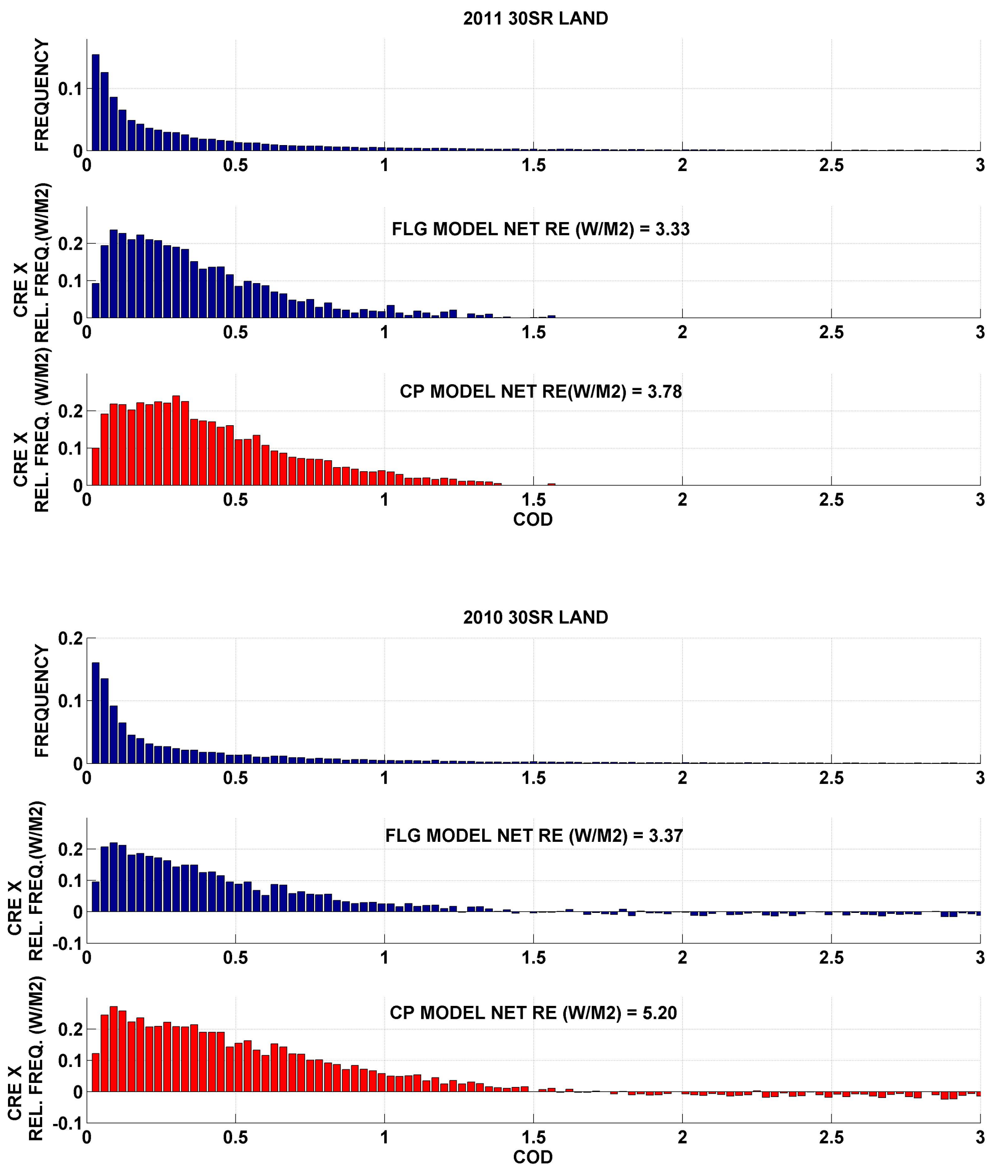


Figure 2 Analysis over land (Albedo=0.12) for 30sr solution. Top Panel: CRE vs. COD weighted by occurrence frequency for Corti and Peter(red) and FLG (blue) models on 2011. Bottom Panel: CRE vs. COD weighted by occurrence frequency for Corti and Peter(red) and FLG (blue) models on 2010

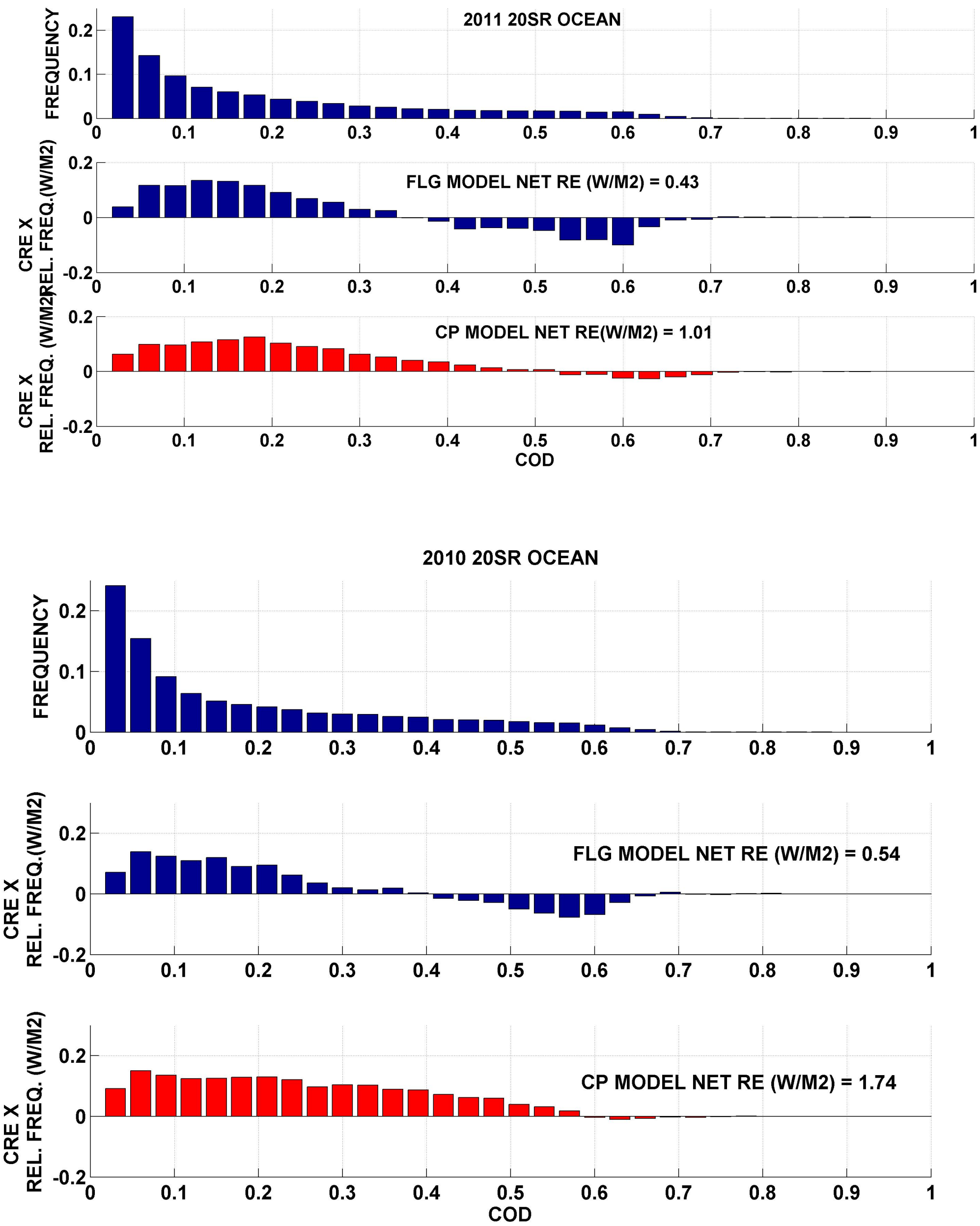
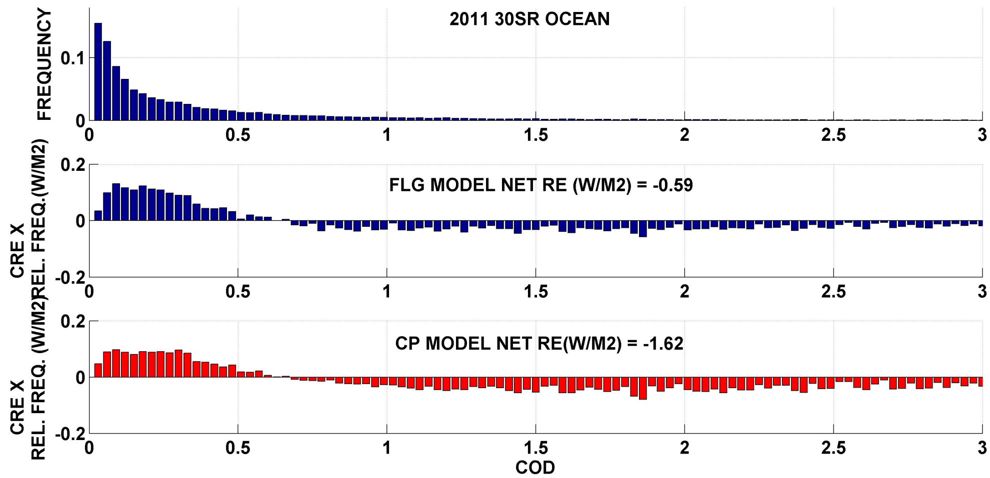


Figure 3 Same as Figure 1, but over the ocean (Albedo=0.05)



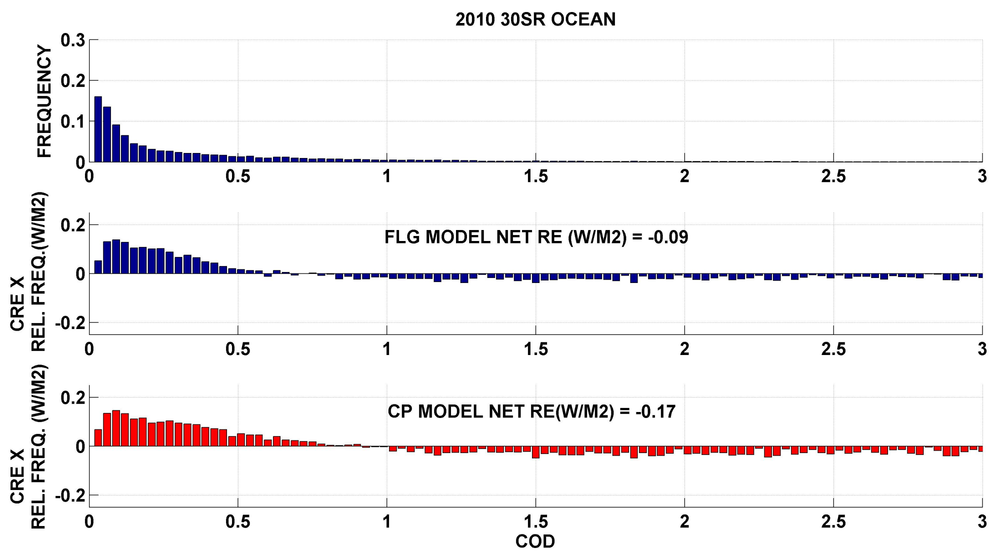


Figure 4 Same as Figure 2, but over the ocean (Albedo=0.05)

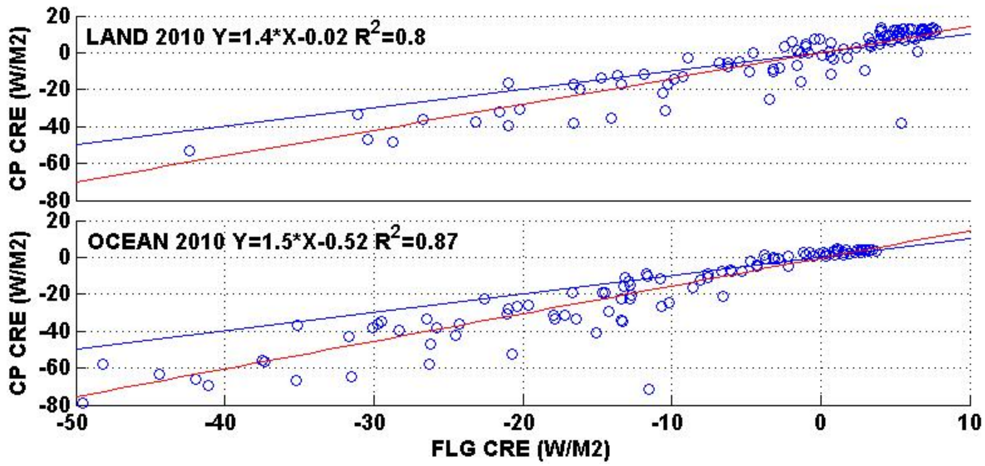


Figure 5 Scatter plot and linear regression for 30sr solution for FLG and CP CRE in 2010 over land (upper panel) and ocean (lower panel)

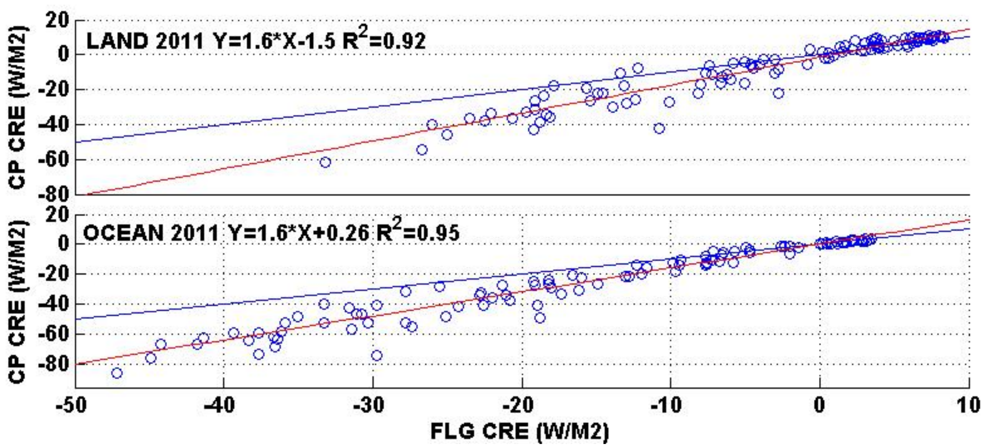


Figure 6 Scatter plot and linear regression for 30sr solution for FLG and CP CRE in 2011 over land (upper panel) and ocean (lower panel)

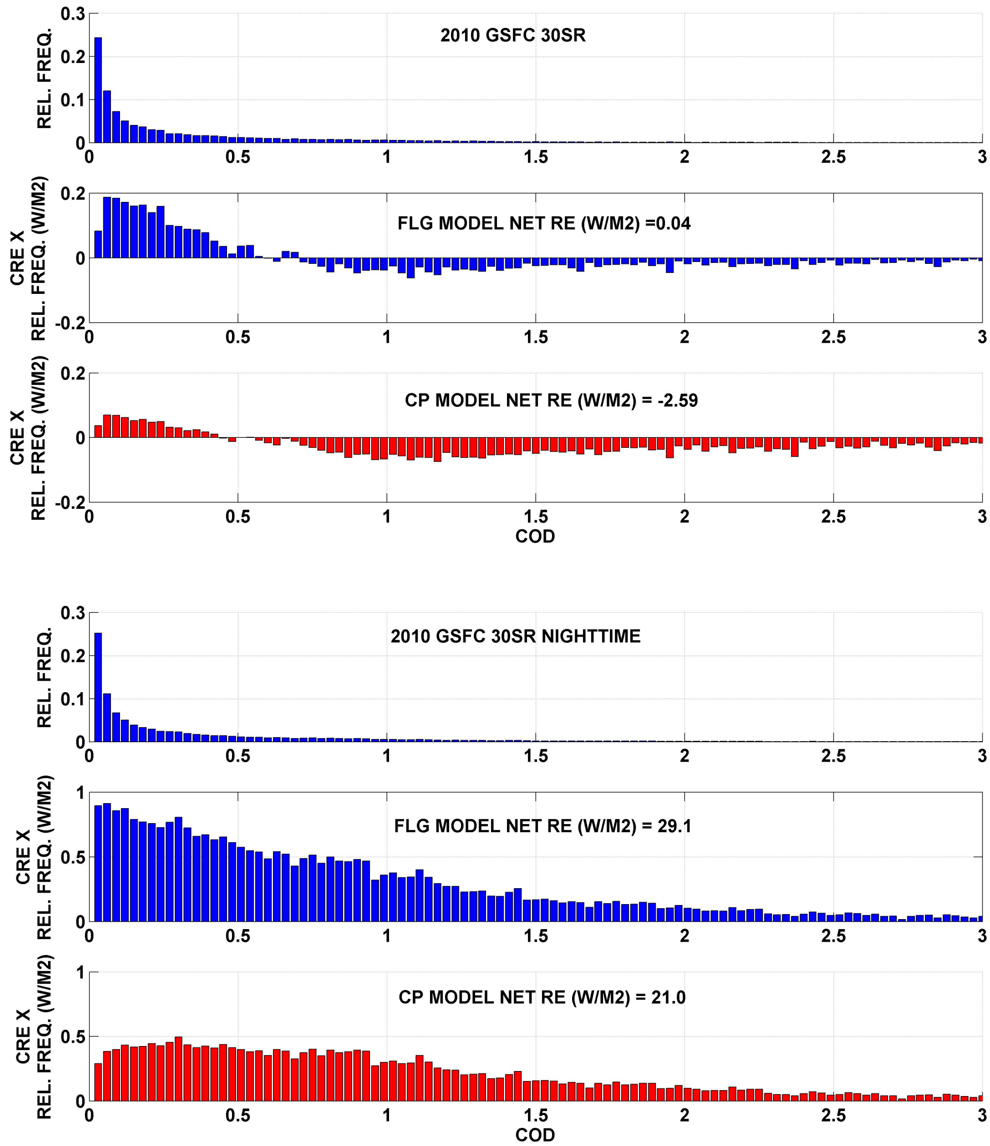


Figure 7 Analysis on 2010 dataset from MPLNET GSFC observational site for 30sr solution daytime (upper panel) and nighttime (lower panel).