Radiative fluxes at high latitudes

Xiaolei Niu,[1] Rachel T. Pinker,[1] and Meghan F. Cronin[2]

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[1] Newly improved satellite products and surface observations provide an opportunity to revisit remote-sensing capabilities for estimating shortwave (SW) radiative fluxes at high latitudes, location of disagreement among models and observations. Estimates of SW fluxes from the Moderate Resolution Imaging Spectro-radiometer (MODIS) are evaluated against land observations from the Baseline Surface Radiation Network (BSRN), from Greenland, and unique buoy measurements. Results show that the MODIS products are in better agreement with observations than those from numerical models. Therefore, the large scale satellite based estimates should be useful for model evaluation and for providing information in formulating energy budgets at high latitudes. **Citation:** Niu, X., R. T. Pinker, and M. F. Cronin (2010), Radiative fluxes at high latitudes, *Geophys. Res. Lett.*, *37*, L20811, doi:10.1029/2010GL044606.

1. Introduction

[2] It is speculated that amplification of greenhouse warming in the Arctic can be partly explained by the feedback associated with the high albedo of polar snow and ice [*Arctic Climate Impacts Assessment*, 2004]. The extent of perennial sea ice has declined 20% since the mid-1970s [*Serreze et al.*, 2007]. The location of the reduced ice in spring and summer coincides with strongest solar radiation. If ice is lost, extra heat can be stored in these regions and remain through winter and reduce ice thickness the following spring. This *ice-albedo feedback* can accelerate the loss of ice.

[3] Trends in clouds and surface properties derived from satellites for the period of 1982 to 1999 show that the Arctic has warmed and become cloudier in spring and summer but has cooled and become less cloudy in winter [*Wang and Key*, 2003]. The increase in spring cloud amount radiatively balances changes in surface temperature and albedo, but during summer, fall, and winter, cloud forcing has tended toward increased cooling. Investigations using field data from the Arctic Alaska [*Chapin et al.*, 2005] indicate that a lengthening of the snow-free season associated with the vegetation and summer albedo changes has increased regional warming by about 3 W m^{-2} decade^{-1}. This heating more than offsets the cooling caused by increased cloudiness.

[4] Reduced ice in spring and summer coincides with strongest solar radiation, of which ice is an excellent reflector. If enough ice is lost to allow sufficient extra heat to enter into the Polar Regions and reduce ice thickness the following spring, the ice-albedo feedback will accelerate the loss of ice. Having accurate estimates of shortwave (SW) fluxes is important for investigating causes of ice loss.

[5] The Polar Region is data sparse with very few in-situ observations and therefore, re-analysis data or satellite observations are a common source of information on radiative fluxes. Previous studies [*Liu et al.*, 2005] indicate that the surface downward SW radiative fluxes derived from satellites are more accurate than the two main re-analysis datasets (National Centers for Environmental Prediction (NCEP) and European Centre for Medium-Range Weather Forecasts (ECMWF)), due to the better representation of cloud properties in the satellite products. During the Surface Heat Budget and the Arctic Ocean (SHEBA) project it was shown that satellite-based analysis may provide downward SW (long wave) fluxes to within ~10–40 (~10–30) W/m^2 as compared with ground observations [*Perovich et al.*, 2007]. The comparison of the surface energy budget over the Arctic (70–90°N) from 20 coupled models for the Intergovernmental Panel on Climate Change (IPCC) fourth Assessment with 5 observationally based estimates and re-analysis shows that the simulation of the Arctic surface energy budget has large bias in climate models, largest differences are located over the marginal ice zones [*Sorteberg et al.*, 2007].

2. Needs

[6] Large scale estimates of radiative fluxes from satellite observations are available at scales ranging from 25 km to 2.5° [*Wang and Key*, 2005; *Zhang et al.*, 2004; *Wang and Pinker*, 2009]. To improve the representation of variability in ice extent in the inference schemes for SW radiative fluxes, it is desirable to increase the spatial resolution of the satellite observations and the representation of surface and atmospheric properties in these regions. Observations made from MODIS are well suited to meet such needs since all needed parameters for inferring such fluxes are observed from the same satellite system simultaneously and there are several overpasses per day at the higher latitudes that represent diurnal variability. The approach that was developed can be implemented at different scales. Relevant MODIS information is available at both a 1° scale and at 5 km scale. In the present study we present results from implementation at 1° resolution since at this resolution longer time series could be derived which provided an opportunity for a more robust evaluation against ground observations. An example of the 1° product for the North and South Poles for respective summer months averaged over three years is illustrated in Figure 1. During the summer, the South Pole land-ocean flux contrast is greater than the contrast at the North Pole and the amount of radiation over the South Pole is greater than over the North pole, which is consistent

[1]Department of Atmospheric and Oceanic Science, University of Maryland, College Park, Maryland, USA.
[2]Pacific Marine Environmental Laboratory, NOAA, Seattle, Washington, USA.

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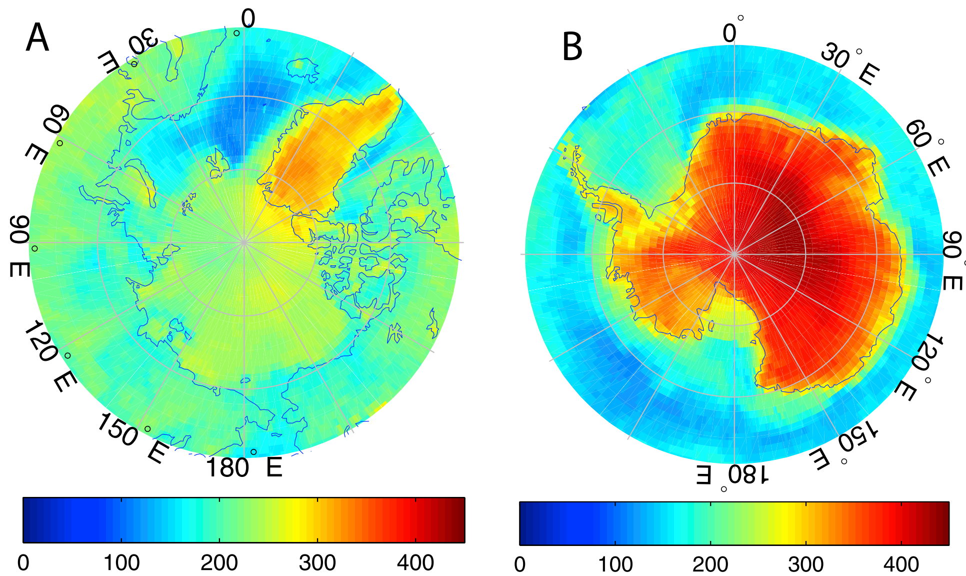

Figure 1. Monthly mean surface downward SW radiation estimated from UMD_MODIS (left) for the North Polar region for July; and (right) for the South Polar region for January, both during (2003–2005).

with the findings of *Kato et al.* [2006] who report that the average cloud fraction for land is about 0.45 over South Pole and about 0.7 over North Pole, but for ocean about 0.9 over the South Pole and about 0.8 over the North Pole.

3. Advantages of MODIS for Improving SW Radiation Budget

[7] Instruments onboard the new generations of sun synchronous satellites tend to have higher spatial and spectral resolution than those on earlier satellites, thus improving capabilities to detect atmospheric and surface parameters. The Moderate Resolution Imaging Spectro-radiometer (MODIS) instrument onboard the Terra and Aqua satellites is a state-of-the-art sensor with 36 spectral bands with an onboard calibration of both solar and infrared bands. The wide spectral range (0.41–14.24 μm), frequent global coverage (one to two days revisit), and high spatial resolution (250 m for two bands, 500 m for five bands and 1000 m for 29 bands), permit global monitoring of atmospheric profiles, column water vapor amount, aerosol and cloud properties, and surface conditions at higher accuracy and consistency than previous Earth Observation Imagers [*King et al.*, 1992].

[8] An inference scheme was developed to utilize information from MODIS instruments to estimate spectral SW radiative fluxes (UMD_MODIS) [*Wang and Pinker*, 2009]. The model was implemented with MODIS products at 1° spatial resolution from Terra and Aqua and as well as at the 5 km resolution [*Su et al.*, 2008]. Extensive evaluation of the 1° product against ground measurements over ocean and land sites both at monthly and daily time scales has been performed. Over oceans the Pilot Research Moored Array in the Atlantic (PIRATA) and the Tropical Atmosphere Ocean (TAO) Triangle Trans-Ocean Buoy Network (TRITON) Array were used; over land the Baseline Surface Radiation Network (BSRN) was used. Evaluation of monthly mean surface downward shortwave flux estimated using the UMD_MODIS model against PIRATA and TAO/TRITON buoy observations (January 2003–December 2005) against PIRATA and TAO/TRITON buoy observations (January 2003–December 2005) has shown for the PIRATA array the correlation coefficient was 0.90, RMSE 13 (5%) and bias 2 (1%). For the TAO/TRITON Array the corresponding values were 0.94, 11 (5%) and −1 (0%). Details are given by *Pinker et al.* [2009].

4. Evaluation of MODIS SW Fluxes at High Latitudes: Preliminary Results

4.1. Data Used

[9] MODIS based estimate of surface SW fluxes at high latitudes are evaluated against Baseline Surface Radiation Network (BSRN) observing stations (http://www.bsrn.awi.de/) (Table 1) and against buoy observations. Due to the lack of buoy observations at very high latitudes, observations "as far north as possible" were used. The following four buoys observe radiative fluxes and will be used:

[10] 1. KEO mooring site (http://www.pmel.noaa.gov/keo/index.html) The NOAA Kuroshio Extension Observatory (KEO) moored buoy is located in the recirculation gyre south of the Kuroshio Extension at the nominal position of 144.6°E, 32.4°N. Data for the following periods will be used: Period 1: June 16, 2004 ~ Nov. 9, 2005; Period 2:

Table 1. Information on High Latitude BSRN Sites Used

BSRN Site	Abbreviation	Latitude	Longitude
NY-Ålesund, Spitsbergen	NYA	78.93°N	11.95°E
Barrow, Alaska	BAR	71.32°N	156.61°W
Georg von Neumayer, Antarctica	GVN	70.65°S	8.25°W
Syowa, Cosmonaut Sea	SYO	69.01°S	39.59°E
South Pole, Antarctica	SPO	89.98°S	24.80°W
Lerwick, United Kingdom	LER	60.13°N	1.18°W

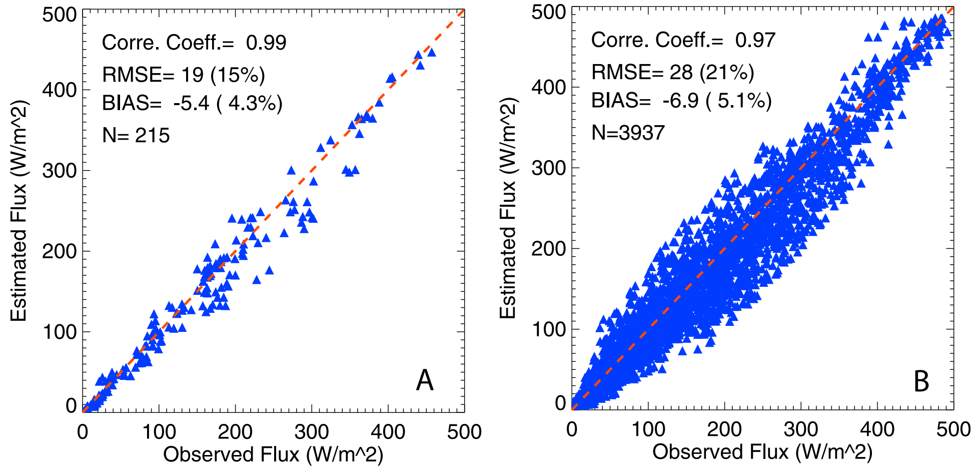

Figure 2. (a) Evaluations of monthly mean downward SW fluxes estimated from UMD_MODIS at six high latitude sites as listed in Table 1 for the period 2003–2006. (b) Same as Figure 2a for daily time scale. Points outside 3-std were removed (2.27% for monthly means and 1.47% for daily means).

May 27, 2006 ~ Apr. 16, 2007; Period 3: Sep. 26, 2007 ~ June 29, 2009 and Sep. 6 ~ 18, 2009.

[11] 2. JKEO mooring site (http://www.jamstec.go.jp/iorgc/ocorp/ktsfg/data/jkeo/).The JAMSTEC Kuroshio Extension Observatory (JKEO) moored buoy is nominally located at 38°N, 146.5°E north of the Kuroshio Extension region (KEO). There are 4 phases of development for the buoys. For the phase 1, IORGC/JAMSTEC deployed a surface buoy (JKEO1) under collaboration with PMEL/NOAA. Data for the following periods will be used: Period 1: Feb. 18 ~ Sep. 15, 2007; Period 2: Oct. 5, 2007 ~ Jan. 25, 2008. For Phase 2, beginning Feb 29, 2008, IORGC/JAMSTEC replaced the PMEL-designed buoy with the K-TRITON developed by MARITEC/JAMSTEC. Data for the following periods will be used: Period 1: Feb. 29 ~ Sep. 4, 2008, Period 2: Nov. 12, 2008 ~ Aug. 27, 2009; Period 3: Aug. 29 ~ Dec. 31, 2009. The movement of the KEO and JKEO buoys is within the 1° footprint of the satellite data so no adjustments were made for the exact location.

[12] 3. CLIVAR Mode Water Dynamic Experiment (CLIMODE) buoys (http://uop.whoi.edu/projects/CLIMODE/climode.html). The CLIMODE buoy is located at 38°N, 65°W and The project aimed to study the dynamics of Eighteen Degree Water (EDW), the subtropical mode water of the North Atlantic. Data for the following periods will be used: Nov. 14, 2005 ~ Dec. 31, 2006.

[13] 4. PAPA mooring site (http://www.pmel.noaa.gov/stnP/index.html). The Ocean Station Papa surface mooring was developed at the Pacific Marine Environmental Laboratory (PMEL) for the harsh conditions of the North Pacific region (http://www.pmel.noaa.gov/). The nominal position of this buoy was (50°N, 145°W). Data for the following periods will be used: Period 1: June 8, 2007 ~ Nov. 10, 2008; Period 2: June 15, 2009 ~ Dec. 31, 2009.

[14] 5. Summit, Greenland site (72.58°N, 38.48°W) is at an elevation of 3208 m. Surface observations were taken under the International Arctic Systems for Observing the Atmosphere Observing Sites (IASOA) project-Greenland Climate Network (GC-Net) (http://iasoa.org/iasoa/index.php?option=com_content&task=view&id=85&Itemid=123 or http://cires.colorado.edu/science/groups/steffen/gcnet/). More information on GC-NET is given by *Steffen et al.* [1996]. Evaluations was done for period 2003 ~ 2007.

4.2. Results

4.2.1. BSRN Sites

[15] Six BSRN stations, considered of highest available quality, as listed in Table 1 were used in the evaluation of the MODIS products. The evaluation was done for a four year period, both at daily and monthly time scales (Figure 2). For the monthly time scale, the correlation was 0.99, the RMS 19 W/m^2 (about 15% of the mean value), while the bias was −5.4 W/m^2 (about 4.3%). At the daily time scale, the respective statistics were 0.97, 28 (21%) and −6.9 (5.1%). Results over land as reported by *Pinker et al.* [2009] for 18 BSRN stations are: for daily averages the bias is −3 W/m^2 and the RMSE is 21 W/m^2.

4.2.2. Buoys

[16] Evaluations of daily averaged surface downward SW fluxes estimated from UMD_MODIS against surface observations at the KEO, JKEO, CLIMODE, and PAPA buoys are presented in Figure 3. Cases where estimates were outside the range of 3 stds were eliminated. The percentage of used observations is indicated in Figures 3a–3d. As evident, the bias is −2.4 W/m^2 (about 1.4% of mean value), 4.5 W/m^2 (3.2%), 7.3 W/m^2 (5.3%), −6.8 W/m^2 (6.2%) for buoys of KEO, JKEO, CLIMODE, and Papa, respectively. The RMS values are 38.1, 29.6, 29.6, 22.8 W/m^2 for the 4 buoys, which are about 21% of mean value. In Figure 4 we show the time series of daily averaged surface downward SW fluxes estimated from UMD_MODIS and as observed at the KEO, JKEO, CLIMODE, and PAPA buoys. The variations of UMD_MODIS estimated fluxes fit well with the observations for the 4 buoys.

[17] *Tomita et al.* [2010] conducted a comprehensive comparison of all the observed parameters from KEO and JKEO including radiative fluxes against the Japanese Ocean Flux data sets with use of Remote Sensing Observations (J-OFURO2). They found that the daily averaged downward SW radiative fluxes of J-OFURO2 for period of Jun.

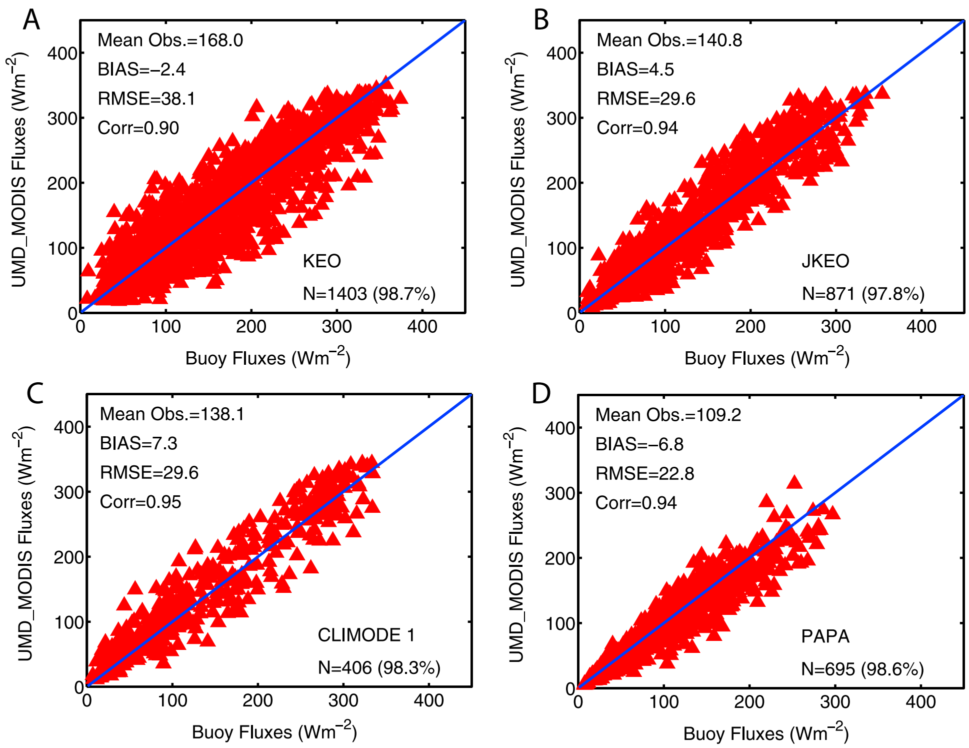

Figure 3. Evaluation of daily averaged surface downward SWR estimated from UMD_MODIS against buoy observations at (a) KEO (32.4°N, 144.6°E), (b) JKEO (38°N, 146.5°E), (c) CLIMODE (38°N, 65°W), and (d) PAPA (50°N, 145°W). Cases were eliminated when outside of 3 stds.

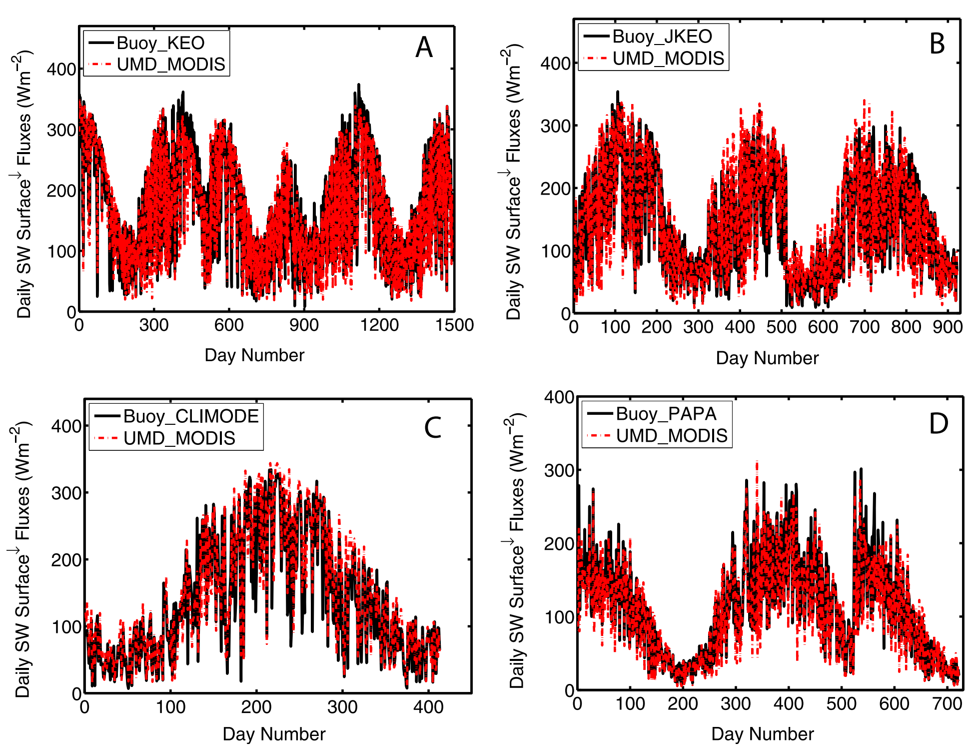

Figure 4. Time series of daily averaged surface downward SWR estimated from UMD_MODIS (red dash line) against buoy observations (black solid line) at (a) KEO (32.4°N, 144.6°E), (b) JKEO (38°N, 146.5°E), (c) CLIMODE (38°N, 65°W), and (d) PAPA (50°N, 145°W).

2004 to Oct. 2006 (633 days) have small bias (0.3 W/m^2 for all days, −4.1 W/m^2 for winter, and 3.5 W/m^2 for summer) and have RMS of 36.7 for all days, 21.4 for winter, and 43.3 W/m^2 for summer. *Kubota et al.* [2008] compared KEO observations against the National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) reanalysis (NRA1), the NCEP/Department of Energy reanalysis (NRA2) data. They found that both re-analyses overestimated the daily averaged downward SW radiative fluxes: bias of 17 W/m^2 for NRA1 and 4 W/m^2 for NRA2; RMS of 52 for NRA1 and 41 W/m^2 for NRA2; and correlation of 0.8 for NRA1 and 0.88 for NRA2.

4.2.3. Summit, Greenland

[18] The station of Summit in Greenland, which is an automatic weather station, was used for the evaluation of the MODIS SW fluxes. The evaluation is done for the period of 2003–2007 at daily time scale (Figure S1 of the auxiliary material).[1] The correlation is 0.99, the RMS 24.3 W/m^2 (about 14% of the mean value), while the bias is −5.7 W/m^2 (about 3.4%).

5. Summary

[19] The quality of information on surface SW radiative fluxes at high latitudes as derived from MODIS observations from both Terra and Aqua at monthly and daily time scales was evaluated. Used were observations from the BSRN network over land and from buoys that as yet, have not been used extensively. The resolution of the satellite products is 1° and as such, not optimal for sites which are mostly coastal (the case for high latitude land sites). Possibly, due to the "homogeneity" of the oceanic sites the results for the buoy observations are comparable to those over the land locations. Better agreement (in terms of correlation and RMS) between the MODIS estimates over land than over ocean sites at lower latitudes is evident, possibly, due to the fact that the land sites are homogeneous [*Pinker et al.*, 2009]. Other possibilities include lower quality of ground observations at high latitudes due to the harsh environment, lower quality satellite retrievals due to the lower quality of MODIS products at this region (such as difficulties associated with cloud detection over snow, low sun angles) or the higher errors in atmospheric input parameters such as water vapor which is low at high latitudes. Another possibility is that the inference scheme has not been optimized for high latitudes.

[20] At high latitudes where the variability of ice extent is an issue, it is believed that the high resolution 5 km product from MODIS is best suited to properly estimate the amount of radiant energy reaching the surface in part because of improved specification of the underlying surface in the inference scheme. It is believed that the accuracy of the fluxes in these regions can be improved by utilizing the high resolution MODIS products, updated inference schemes, and high quality ground observations to identify possible shortcomings. In particular, there is a need to utilize more accurate information on surface and atmospheric conditions, improved narrow to broadband transformations (that use realistic land classifications), and newly available bidirectional distribution functions (BRDF) (e.g., from CERES or MISER). Observations from CloudSat can be used for evaluation of the MODIS based methodology.

[1]Auxiliary materials are available in the HTML. doi:10.1029/2010GL044606.

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M. F. Cronin, Pacific Marine Environmental Laboratory, NOAA, 7600 Sand Point Way NE, Bldg. 3, Seattle, WA 98115, USA.

X. Niu and R. T. Pinker, Department of Atmospheric and Oceanic Science, University of Maryland, Space Sciences Building, College Park, MD 20742, USA. (pinker@atmos.umd.edu)