Toward a Long-Term Consistent Ocean Surface PAR Product from MODIS and VIIRS Data

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1. INTRODUCTION

-Photosynthetically Available Radiation (PAR) is defined as the quantum energy flux from the Sun in the spectral range 400-700 nm. It is expressed in Einstein/m^2/day. Daily PAR is the average flux during a day (24 hours).

-PAR controls the growth of phytoplankton. It ultimately regulates the composition and evolution of marine ecosystems.

-Knowing the distribution of PAR over the oceans, spatially and temporally, is critical to understanding biogeochemical cycles of carbon, nutrients, and oxygen, and addressing climate and global change issues, such as the fate of anthropogenic atmospheric carbon dioxide.

2. SATELLITE ESTIMATION

Objective

-To produce a long-term, consistent time series of daily PAR over the global oceans from multiple satellite observations (SeaWiFS, MODIS-Aqua, MODIS-Terra, etc.)

Approach/Method

-To estimate daily PAR on a pixel basis from individual satellite instruments, then merge the individual estimates.

-For each instrument, PAR is basically computed as the difference between the incident 400-700 nm solar flux (known) and the reflected flux at the top of the atmosphere (measured).

-Knowledge of pixel composition is not required, eliminating the need for cloud screening and arbitrary assumptions about sub-pixel cloudiness.

Model

-The PAR model uses plane-parallel theory and assumes that the effects of clouds and clear atmosphere can be de-coupled. The planetary atmosphere is therefore modeled as a clear sky atmosphere positioned above a cloud layer.

-The solar flux reaching the ocean surface is given by

$$E = E_{clear}(1 - A)(1 - A_s)^{-1}$$

where A is the albedo of the cloud-surface system and A_s the albedo of the surface, and E_{clear} is the solar flux that would reach the surface in the absence of clouds.

-A is expressed as a function of the radiance measured by the satellite sensor in the PAR spectral range.

Procedure

-A daily PAR estimate is obtained for each instantaneous pixel, assuming the cloud/surface system is stable during the day and corresponds to the satellite observation.

-Daily PAR estimates obtained separately from different orbits are binned using a simple, linear averaging scheme (arithmetical mean), or by weighting the estimates using the cosine of the solar zenith angle.

-Diurnal variability of clouds is accounted for statistically using ISCCP 3-hour climatology of fractional cloud coverage and cloud optical thickness.

-To ensure consistency of the PAR data over time, estimates using data from one, two, or three sensors are compared, and statistical adjustment factors determined.

-Final product combines estimates from individual satellites.

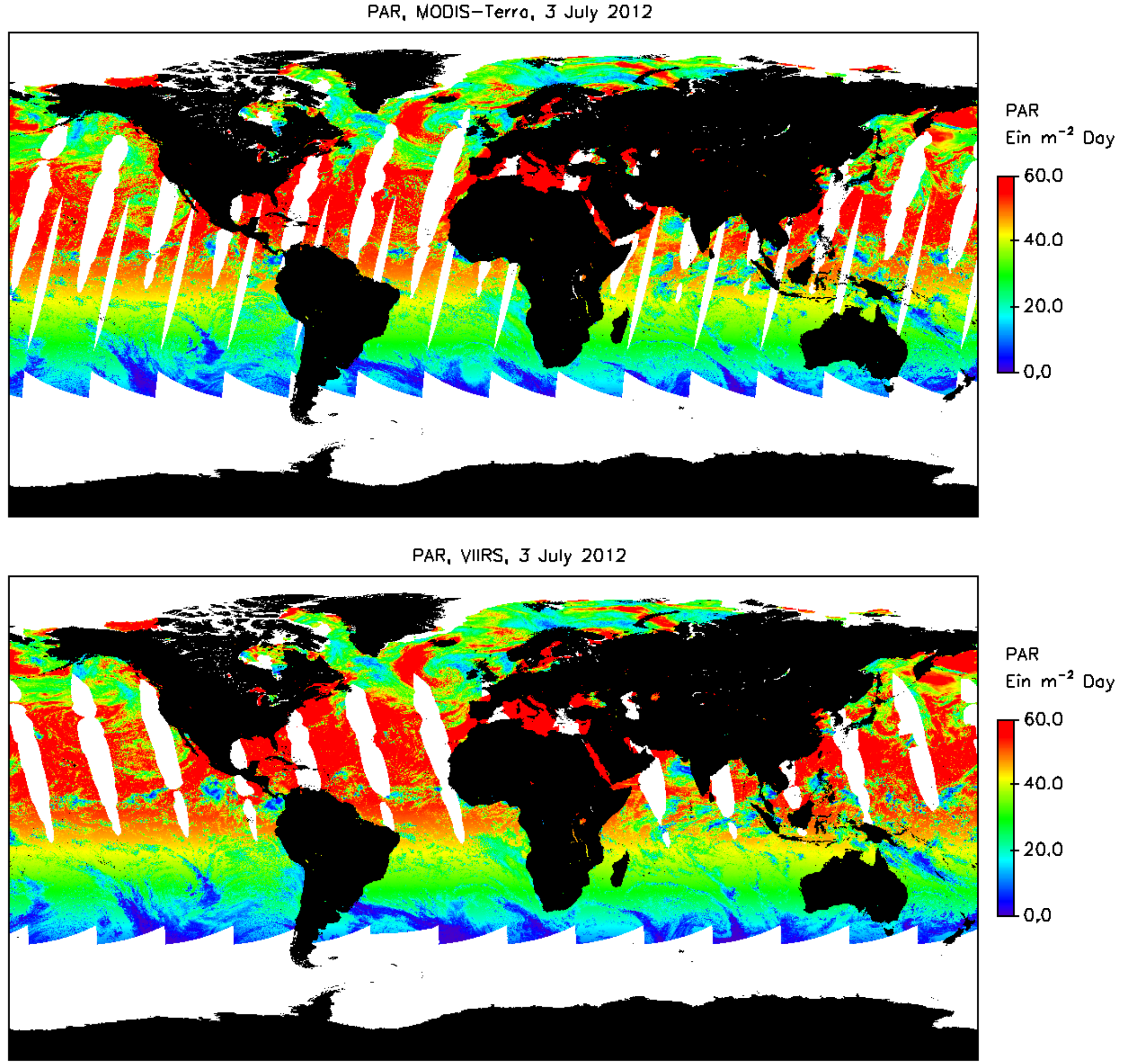


***Figure 1**: Daily PAR products obtained by the NASA OBPG for 3 July 2012. (Top) MODIS-A. (Bottom) VIIRS..*

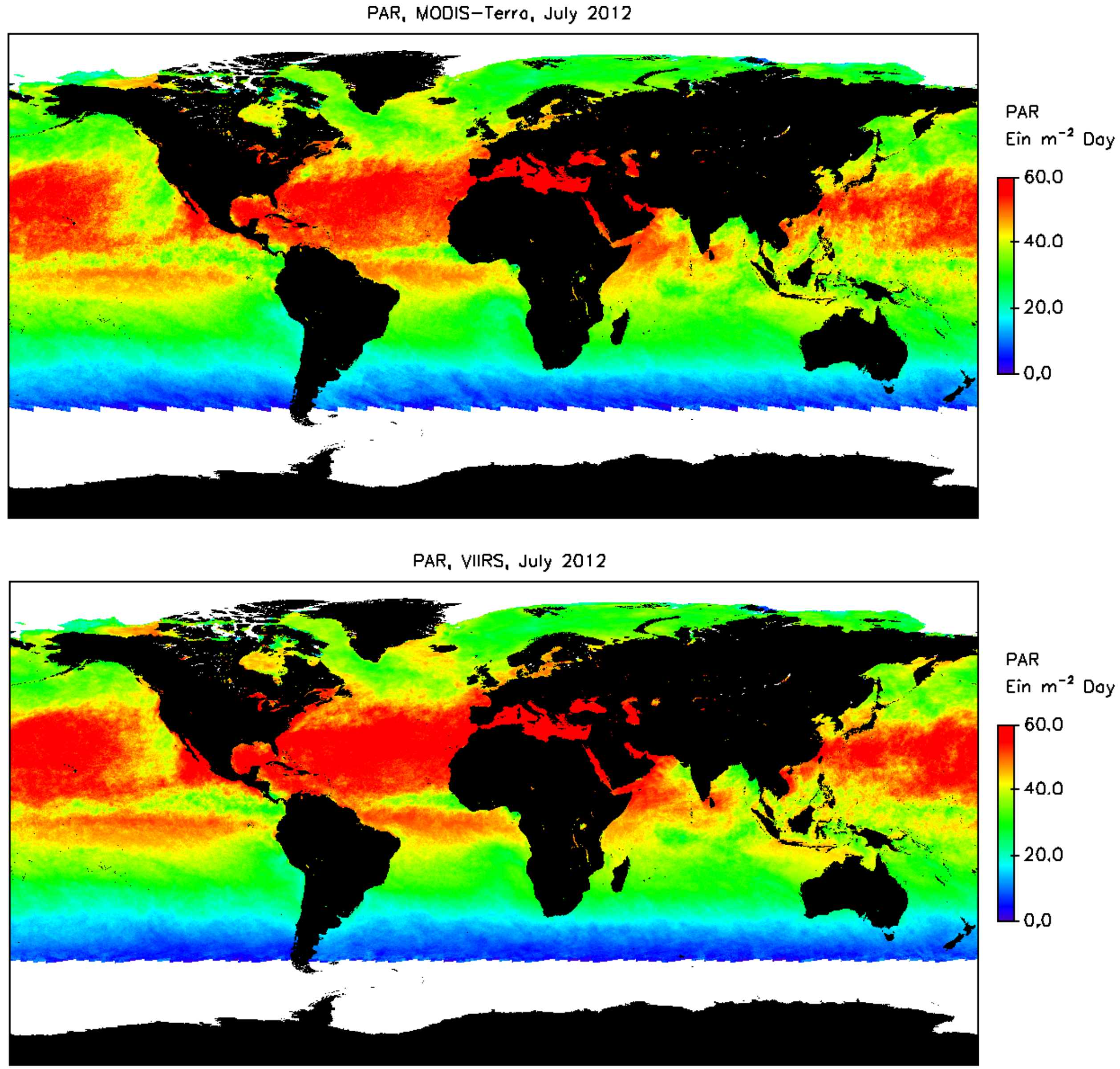


***Figure 2**: Monthly PAR products obtained by the NASA OBPG for July 2012. (Top) MODIS-A. (Bottom) VIIRS.*

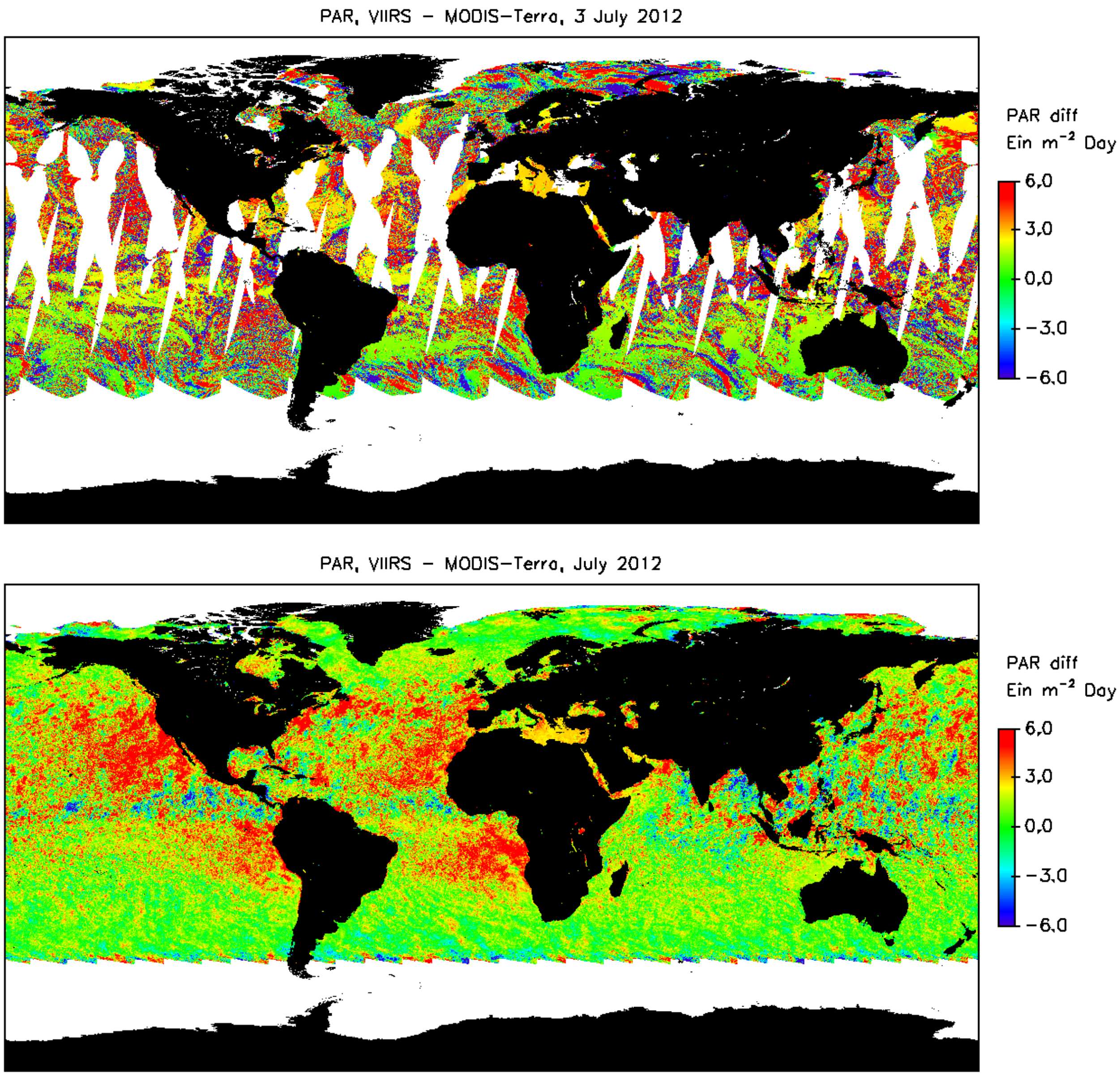


***Figure 3**: Difference between MODIS-Terra and VIIRS PAR products obtained by the NASA OBPG. (Top) 3 July 2012. (Bottom) July 2012).*

3. GENERATION OF A CONSISTENT MODIS/VIIRS RECORD

-PAR values from individual instruments were compared with those from combining three instruments (MODIS-T, MODIS-A, and VIIRS).

-Monthly maps of average differences were computed at 9 km resolution.

-These maps were then used to correct the estimates from individual instruments and produce a consistent multi-year time series of PAR imagery across sensors .

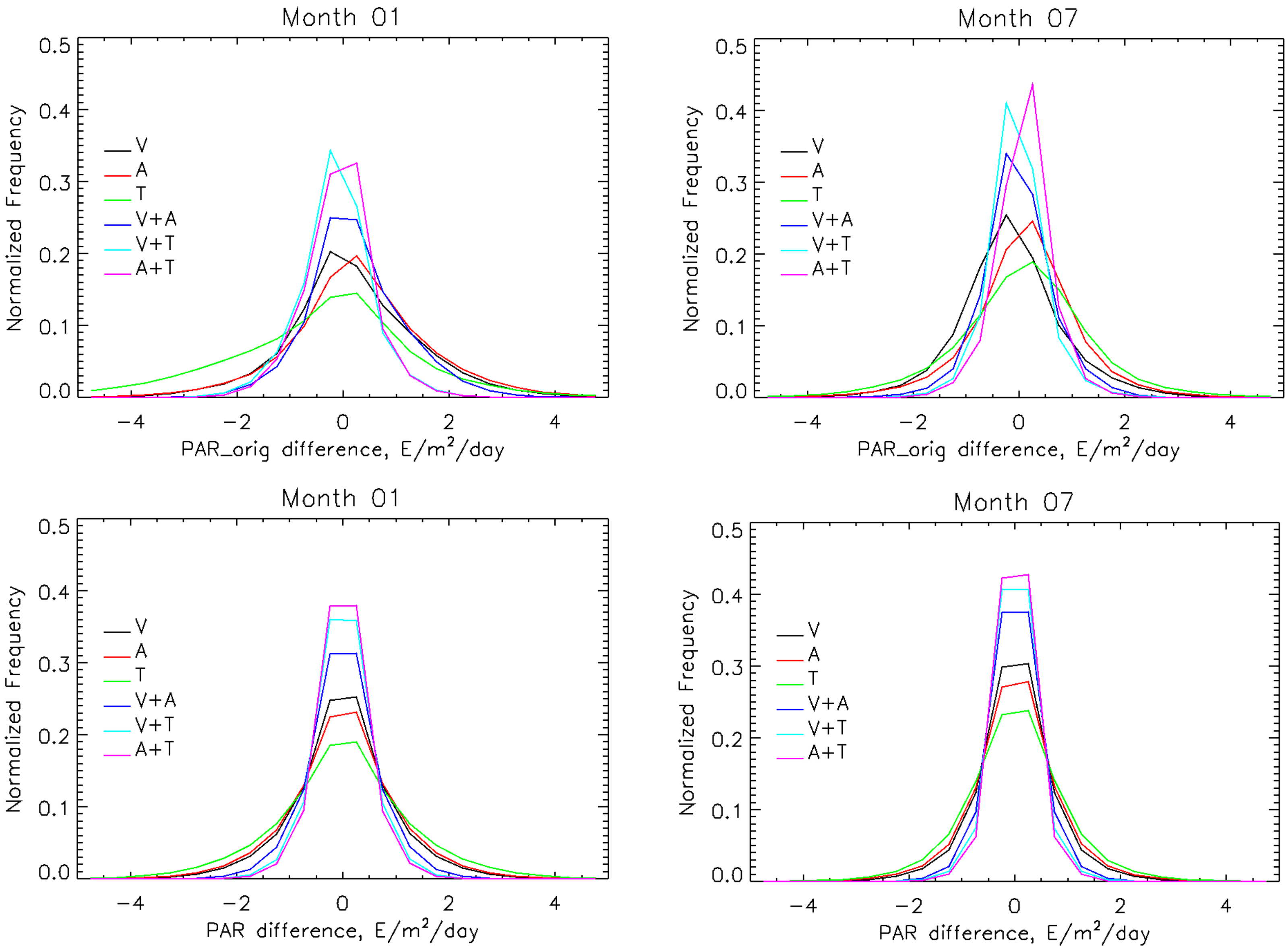


Figure 4: *(Top) Histograms of January and July differences between PAR derived by individual or two instruments and PAR derived by three instruments. (Bottom) Same as Top, but after correction of biases. The histograms are computed with global PAR data from January 2012 to December 2014.*

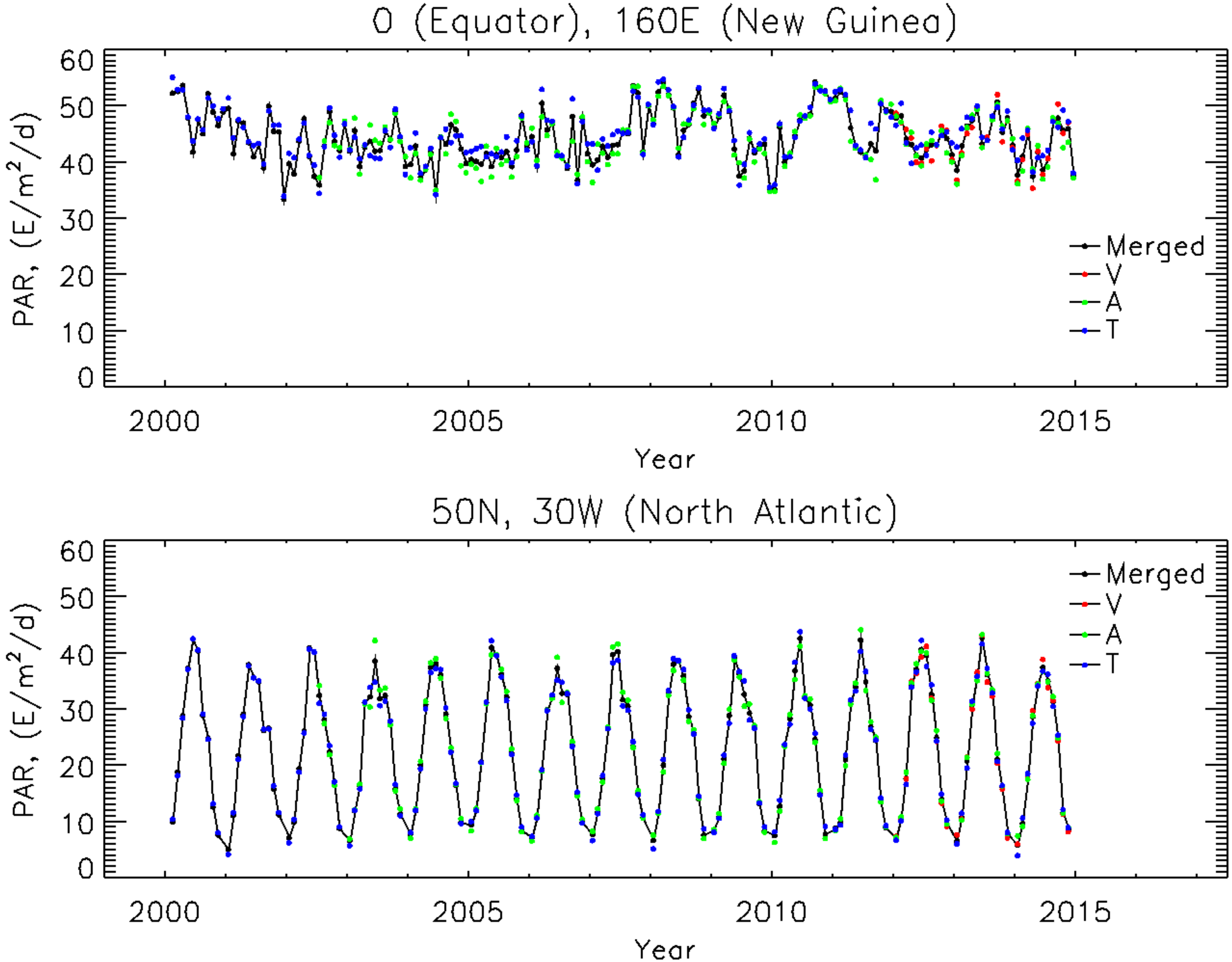


Figure 5: *Time series of monthly PAR data obtained from one, two, or three instruments. (Top) Equator, 160 E. (Bottom) 50 N, 30 W. The values obtained by individual instruments are corrected for biases with respect to three instruments.*

4. ACCOUNTING FOR CLOUD DIURNAL VARIABILITY

-Climatology of cloud optical thickness and fractional coverage (e.g., 3-hourly ISCCP products) may be used to account statistically for diurnal changes in cloudiness.

-The albedo of the cloud/surface system, A, can be approximated by $NA_c + A_s$, where A_c is the cloud albedo. It is replaced in the daily integration scheme by A':

$$A' = (A - A_s)\,[N_{ISCCP}(t)A_c(\tau_{c\text{-}ISCCP}(t))]/[A_c(\tau_{c\text{-}ISCCP}(t_{obs}))N_{ISCCP}(t_{obs})] + A_s$$

where t_{obs} is the satellite observation time, and N_{ISCCP} and $\tau_{c\text{-}ISCCP}$ are the ISCCP fractional cloud coverage and cloud optical thickness.

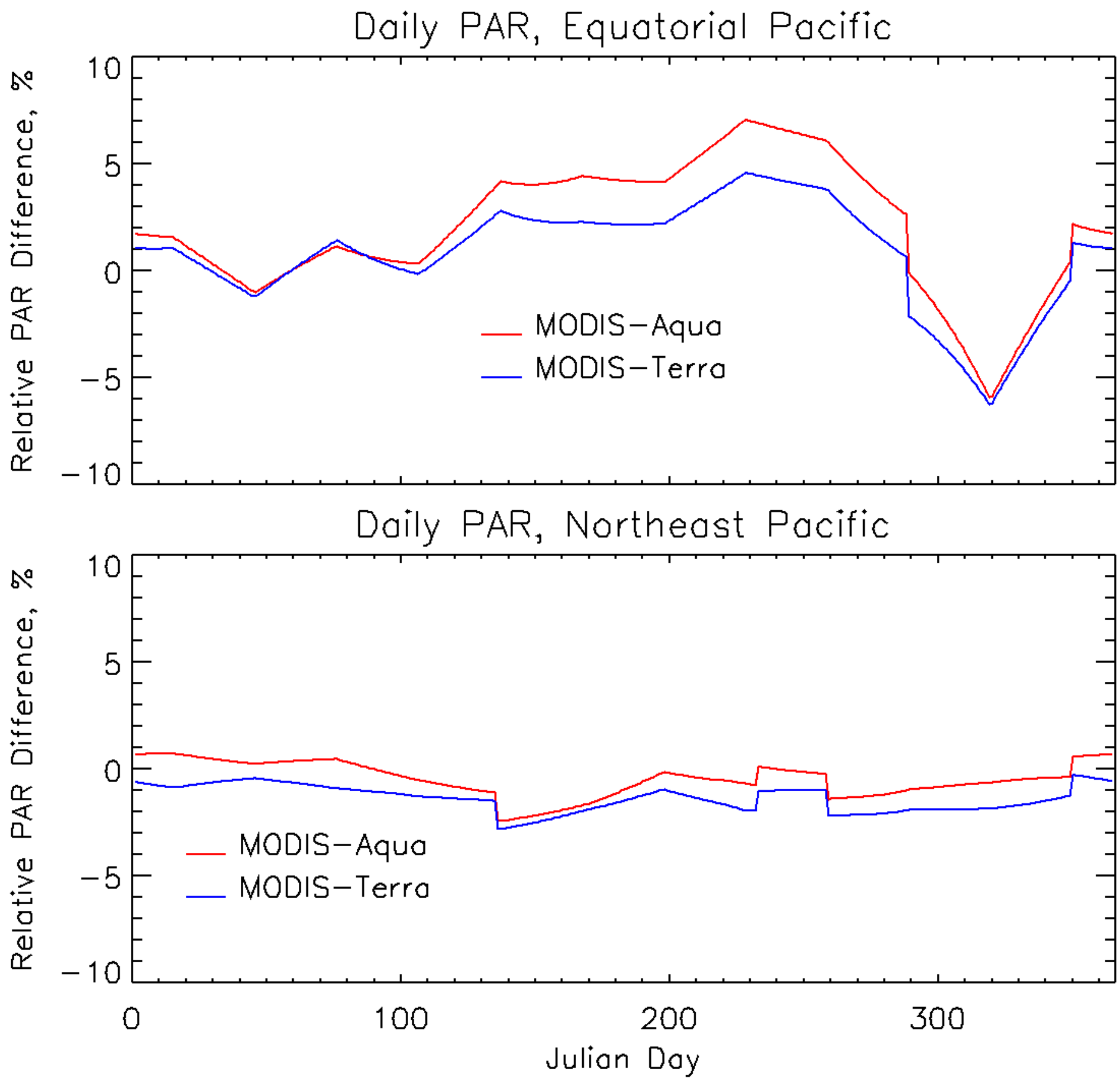


***Figure 6**: Examples of expected PAR correction using ISCCP data in the Equatorial Pacific and Northeastern Atlantic.*

5. EVALUATION AGAINST IN-SITU MEASUREMENTS

-The PAR algorithm/product has been evaluated against in situ measurements from the COVE platform off the west coast of the US (2 PAR sensors, 36.9N-75.7W).

-Other suitable platforms/moorings exist for evaluation, namely:

•BOUSSOLE buoy, Mediterranean Sea, 43.4N-7.90E (since 1999).

•CCE1 and CCE2 moorings off the California coast, 33.5N-122.5W and 24.4N-120.8W (since 2010 and 2011).

•Socheongcho Platform. Yellow Sea, 37.4N-124.7E (since 2015).

•Ieodo Platform, East China Sea, 37.1N-125.2E (installation in June 2015).

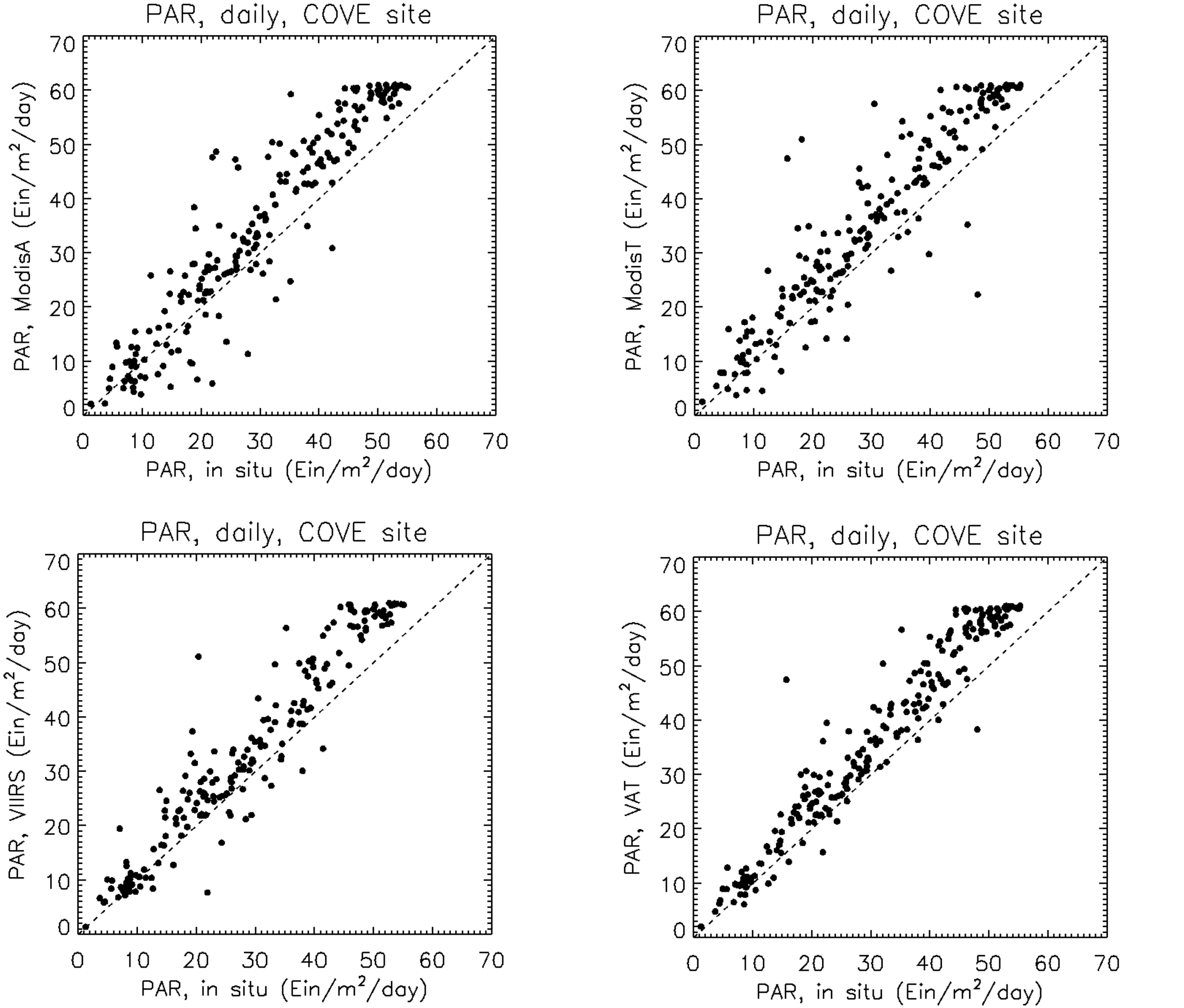


***Figure 7**: Comparison of daily PAR estimated from MODIS-Aqua, MODIS-Terra, VIIRS, and from the 3 instruments, with in situ measurements at the COVE site (2012-2013)*

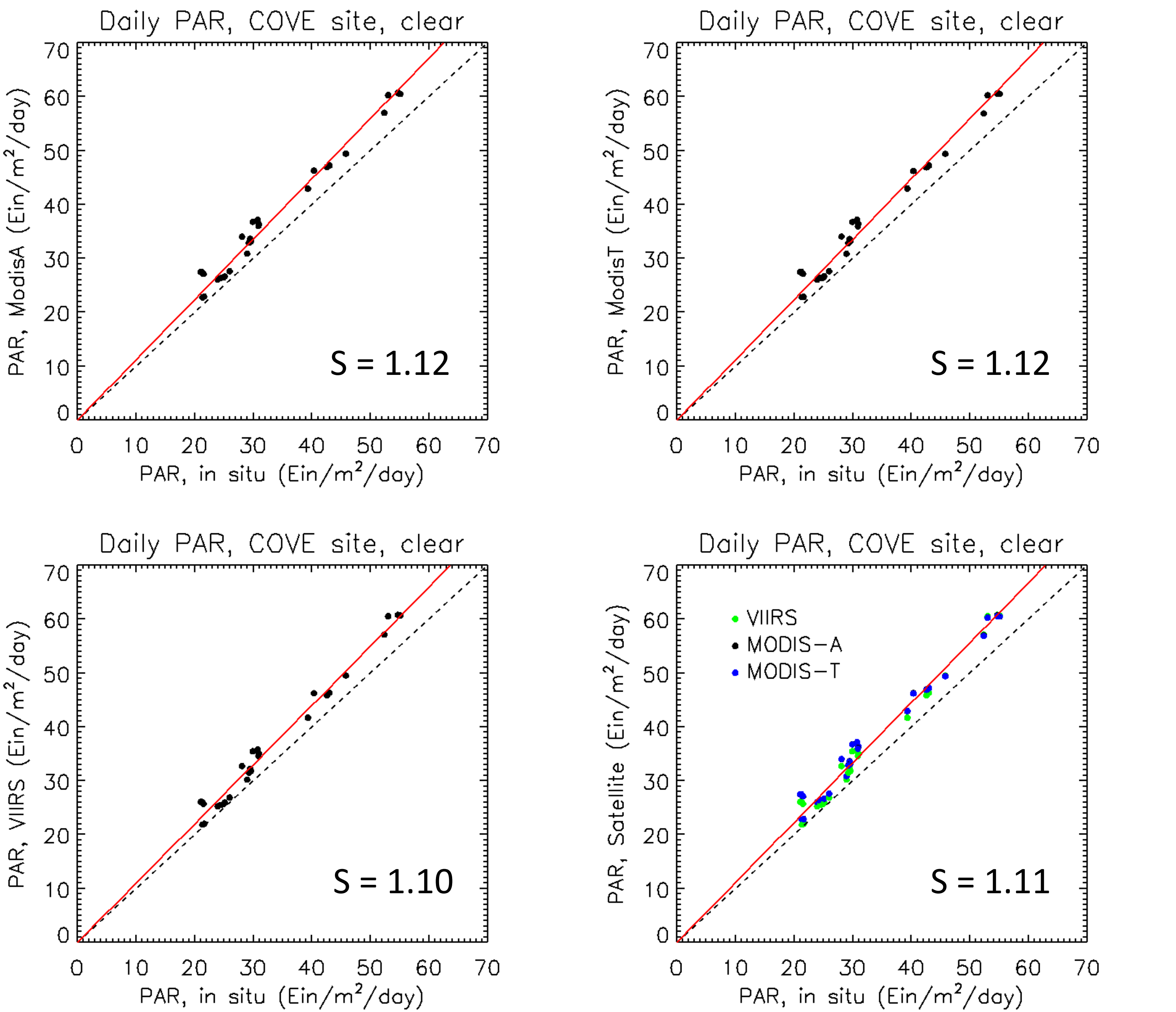


***Figure 8**: Comparison of clear sky daily PAR estimated from MODIS-Aqua, MODIS-Terra, and VIIRS with in situ measurements at the COVE site (2012-2013).*

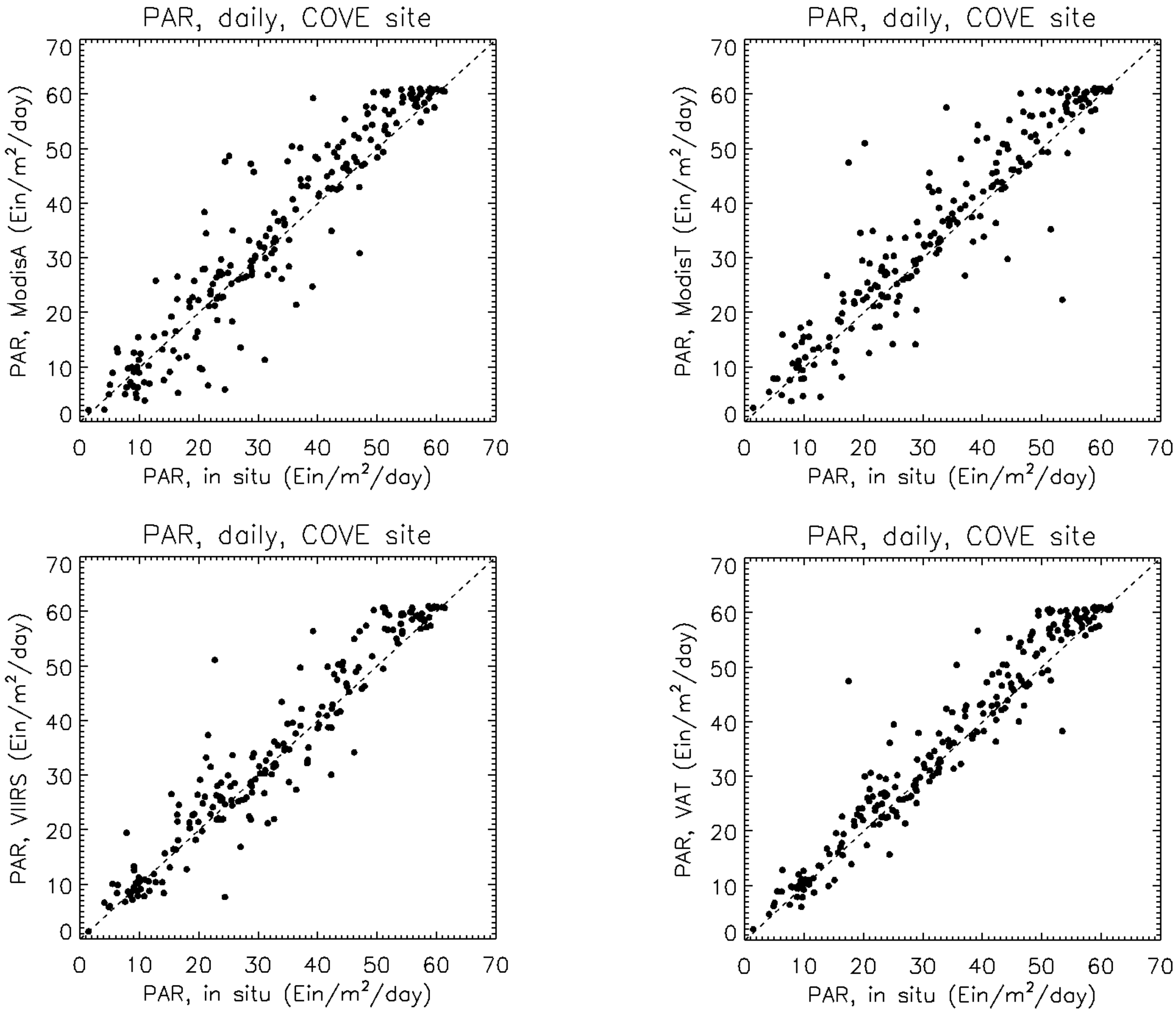


***Figure 9**: Comparison of daily PAR estimated from MODIS-Aqua, MODIS-Terra, VIIRS, and from the 3 instruments, with in situ measurements, after clear sky correction.*

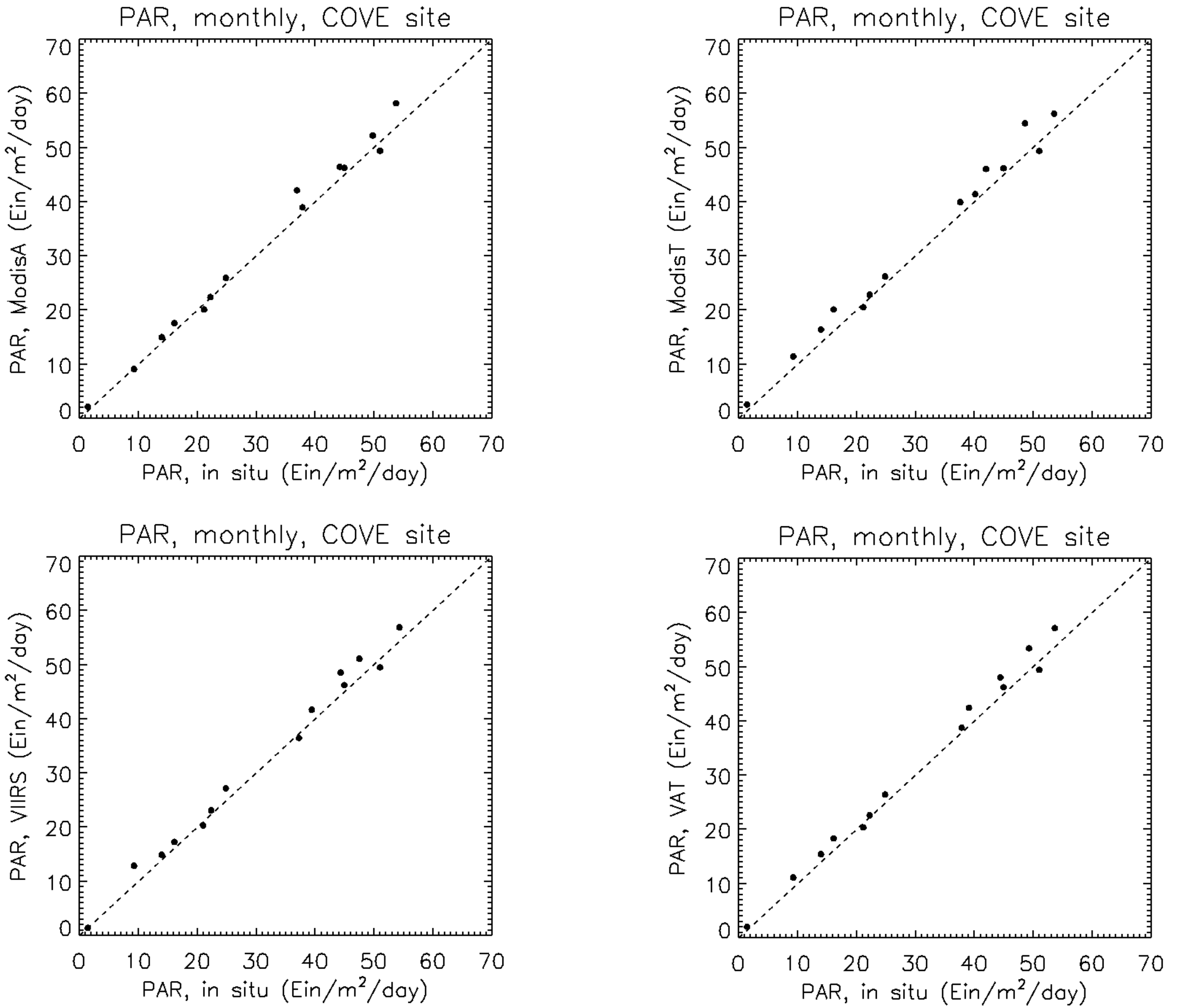


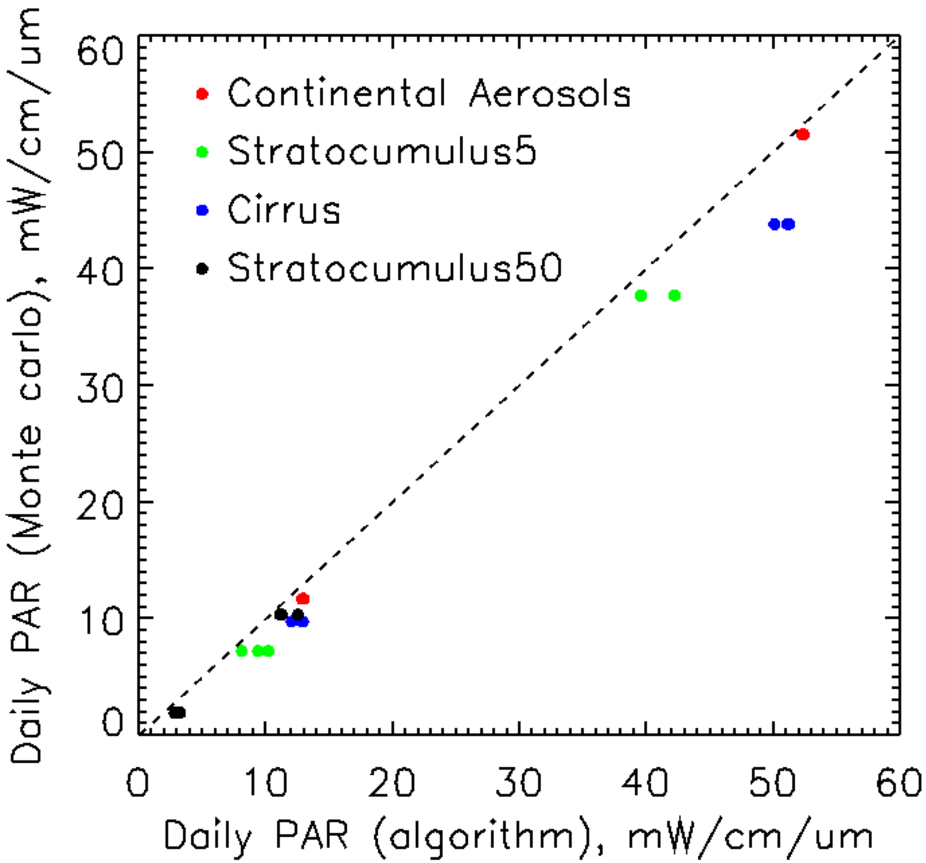
***Figure 10**: Comparison of monthly PAR estimated from MODIS-Aqua, MODIS-Terra, VIIRS, and from the 3 instruments, with in situ measurements, after clear sky correction.*

***Table 1**: Comparison statistics of estimated and measured surface PAR at the COVE site for daily, weekly, and monthly time scales (2012-2013), after clear sky correction. All situations (clear and cloudy) are used in the comparisons.*

Instrument	Daily	Weekly	Monthly
VIIRS	r^2 = 0.913 Bias = 1.61 E/m^2/d (4.9%) RMSD = 5.35 E/m^2/d (16.4%)	r^2 = 0.960 Bias = 1.45 E/m^2/d (4.4%) RMSD = 3.54 E/m^2/d (10.7%)	r^2 = 0.990 Bias = 1.38 E/m^2/d (4.5%) RMSD = 2.20 E/m^2/d (7.2%)
MODIS-Aqua	r^2 = 0.883 Bias = 1.73 E/m^2/d (5.2%) RMSD. = 6.53 E/m^2/d (19.6%)	r^2 = 0.960 Bias = 1.38 E/m^2/d (4.2%) RMSD = 3.57 E/m^2/d (11.0%)	r^2 = 0.988 Bias = 1.28 E/m^2/d (4.2%) RMSD = 2.21 E/m^2/d (7.2%)
MODIS-Terra	r^2 = 0.864 Bias = 2.40 E/m^2/d (7.3%) RMSD = 6.77 E/m^2/d (20.5%)	r^2 = 0.966 Bias = 2.35 E/m^2/d (7.3%) RMSD = 3.76 E/m^2/d (11.6%)	r^2 = 0.988 Bias = 1.89 E/m^2/d (6.2%) RMSD = 2.66 E/m^2/d (8.7%)
V+A+T	r^2 = 0.937 Bias = 2.14 E/m^2/d (6.2%) RMSD= 4.85 E/m^2/d 14.0%)	r^2 = 0.983 Bias = 1.82E/m^2/d (5.5%) RMSD = 2.84 E/m^2/d (8.7%)	r^2 = 0.992 Bias = 1.58 E/m^2/d (5.1%) RMSD = 2.26 E/m^2/d (7.4%)

6. COMPARISON WITH MONTE CARLO CODE

-To evaluate the PAR algorithm theoretically, a tool based on a general Monte Carlo code was developed to simulate satellite radiance and PAR.



<u>Conditions</u>

Continental aerosols
τ_a(862 nm) = 0.1
θ_v = 0, 30, 60 deg., ϕ =90 deg.
01 Jan 2015, 01 July 2015
Sc, τ_c = 5, 50, 2-3 km
Ci, τ_c = 1, 9-10 km
[chl] = 0.1 mg/m^3, V = 5 m/s
O3 = 300 DU, [H2O] = 0.9 g/cm^2

Figure 11*: Comparison between PAR estimated by algorithm and "Exact PAR, for various atmospheres (clear, cloudy) and solar and viewing geometries.*

7. COMPARISON WITH GOCI DATA

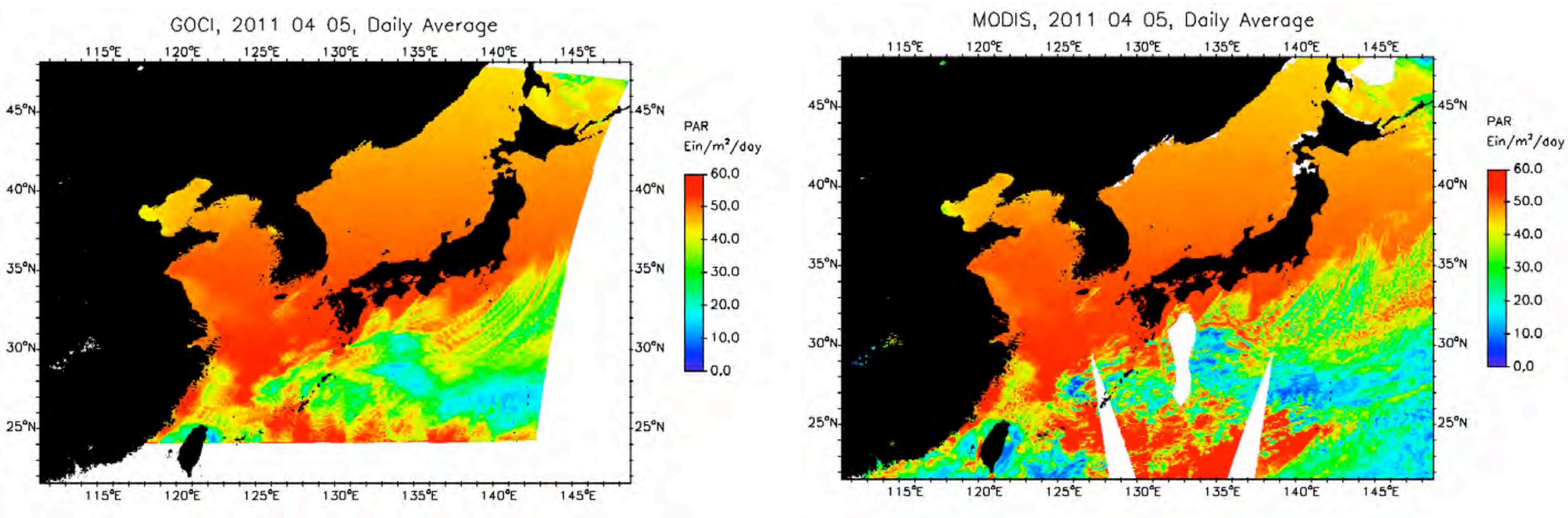


Figure 12: *Daily PAR imagery for April 5, 2011 obtained from GOCI data (top) and MODIS-Aqua and -Terra data (bottom). The GOCI estimates at 0.5 km resolution are remapped onto the MODIS Level 3 4x4 km grid.*

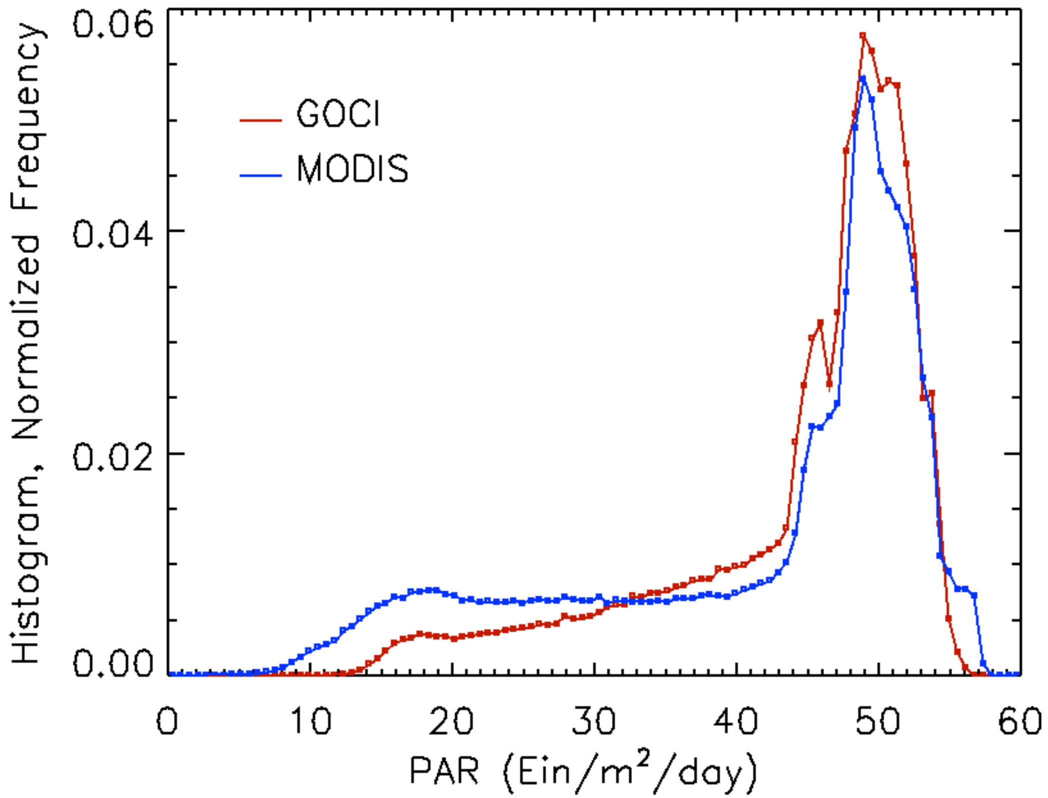


Figure 13: *Histogram of daily PAR values obtained using GOCI observation at 03:16 GMT and all observations during April 5, 2011 (red and blue curves, respectively).*

8. FUTURE WORK

-Extensive evaluation against in-situ measurements at various sites on daily to monthly time scales, individual and combined estimates.

-Comparisons with "exact" calculations, to evaluate theoretically algorithm performance in varied clear/cloudy situations, and make model adjustments.

-Evaluation of the statistical correction of diurnal cloud variability. (GOCI data will be useful for this task.)

-Associate uncertainties to the PAR products on a pixel-by-pixel basis.