

Application of Remotely Sensed Data in the Estimation of Net Radiation at the Earth's Surface in Clear Sky Conditions

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Abstract: This study focuses on the estimation of shortwave and longwave radiation utilizing measured data from the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument on the National Aeronautic and Space Administration (NASA's) Terra / Aqua satellites in clear sky conditions. The net radiation is the vector sum of the shortwave and longwave radiation coming towards and going away from the Earth's surface. The study is carried out for a tropical site Kaiga, located in Southern India for the months of March and April representative of the warm season and the months of November and December representative of the cold season in the year 2013. The validity of the net radiation values estimated from MODIS data is assessed by comparing it with simultaneous ground based measurements from the Mini Boundary Layer Masts (MBLMs). The results indicate that the net radiation values estimated by the satellite are well correlated with the ground based measurements ($R^2 = 0.983$). On an average, for the four months of study, the mean absolute error between the satellite and ground based measurements is 35 W m^{-2} where as the RMSE is 50 W m^{-2} . Once validated with ground based measurements, the satellite derived net radiation data can be used for validation of land surface energy balance predicted by atmospheric models.

Keywords: MODIS, MBLM, Net Radiation

1. Introduction

The absorption of solar radiation and emission of terrestrial radiation by the earth and constituents of the atmosphere drive the general circulation in the atmosphere. This general circulation is largely responsible for the earth's weather and climate. Ever since the launch of the first meteorological satellite several decades ago, the estimation of the earth's radiation budget from space remains an important application. The net radiation is the vector sum of the shortwave and longwave radiation coming towards and going away from the Earth's surface. It is an important parameter in the surface energy budget and required for

climate change studies, monitoring weather, estimation of evapotranspiration and agricultural meteorology. Studies on the measurement of land surface energy balance from space have relied on geostationary as well as polar orbiting satellites. The geostationary satellites have high temporal resolution (~ 3 hours) but coarse spatial resolution of the order of $20 - 250 \text{ km}$ [9]. The polar orbiting satellites on the other hand, have superior spatial resolution; however their global coverage is twice a day and hence they are not very suitable for studies on diurnal variation. Utilizing data from multiple satellites and some interpolation techniques one can obtain information on diurnal variation. Data from Moderate Resolution Imaging Spectroradiometer (MODIS) have been used to derive the net radiation in Jiangxi Province, China

and comparison with in situ measurements were carried out [2]. It was seen that a good accuracy is achieved in deriving the longwave, shortwave and net radiation from satellite data and the satellite data are useful in the studies on heat exchanges, environmental, hydrology and ecology research in land areas. Data from the Along Track Scanning Radiometer (ATSR) have also been utilized for the estimation of net longwave and shortwave radiation [14, 15]. Measurements from the Landsat – 5 Thematic Mapper along with a digital elevation model were used to obtain the net shortwave radiation over a 17 km x 17 km area near Manhattan, Kansas [16]. Several studies have utilized remote sensing observations from the Geostationary Observational Environmental Satellite (GOES) and the National Oceanic and Atmospheric Administration (NOAA) - Advanced Very High Resolution Radiometer (AVHRR) for the estimation of shortwave and longwave radiation components [5, 6]. Even though several studies have demonstrated the application of satellite derived data in estimation of energy budget, due to the several sources of error possible, like errors in the retrieval algorithm, errors due to non-uniform field of view of the sensor and several simplifying assumptions in the retrieval algorithm, the satellite data should be first validated with ground based measurements before utilizing them for the estimation of the desired parameters. The present study utilizes remotely sensed data from the MODIS for the estimation of net radiation. In the first part of this study, for estimating net radiation, a model namely Satellite Estimate of Surface Energy Budget (SESEB) in clear sky conditions is developed. Input data required for the model are obtained from the MODIS satellite. The next part of this study is on the validation of the satellite derived net radiation values with ground based measurements. The validation is carried out for four months namely March and April 2013, assumed to represent the warm season in India and the months of November and December 2013, assumed representative of the cold season in India. The ground based measurements are carried out at Kaiga site in Southern India. The present study assumes clear sky conditions.

2. Materials and Methods

This paper is on the comparison of net radiation values estimated by the satellite derived data with ground based measurements. MODIS flies on board the National Aeronautics and Space Administration (NASA's) Terra and Aqua satellites and it acquires data in 36 spectral bands from 0.412 μm to 14.200 μm spanning the visible, infra – red and thermal infra – red wavelengths. The MODIS science team provides data in four sub disciplines namely land, atmosphere, ocean and calibration. In this study, the MODIS geolocation data product namely MOD03 (MYD03), the MODIS atmospheric temperature profile MOD07 (MYD07) and MODIS Land Surface Temperature product MOD11 (MYD11) have been utilized for the estimation of net radiation. Here MOD refers to the data obtained from Terra MODIS and MYD refers to the data obtained from Aqua

MODIS. The MODIS atmospheric temperature profile product MOD07 (MYD07) provides the temperature profile in the atmosphere in twenty vertical levels from 1000 mbar to 5 mbar. The air temperature in the lowest available pressure level (i.e. 1000 mbar or 950 mbar) is used as a surrogate for screen level temperature [1]. At any given location there are two overpasses in a day, each of Terra and Aqua MODIS providing four hours of co – located data for comparison. The values of land surface temperature, emissivity, solar zenith angle, air temperature obtained from Terra / Aqua MODIS are used to estimate the surface net radiation using the energy balance laws [1]. The exact computation of the shortwave and longwave radiation components from satellite requires information about the clear sky transmissivity, as well as the fraction attenuated by uniformly mixed gases, water vapour and aerosols. These computations require the integration of complex radiative transfer models as well as the information about the concentration of gaseous constituents in the atmosphere. To avoid the use of complicated models, several empirical equations have been suggested in literature [3, 8, 9, 10]. The present study utilizes empirical equations for the estimation of short and longwave radiation components. The incoming shortwave radiation ($R_{s\downarrow}$) can be estimated as follows.

$$R_{s\downarrow} = 0.72 \times S_0 \times \cos \theta \quad (1)$$

S_0 = solar constant (1367 W m^{-2})

θ = solar zenith angle

Once the incoming shortwave radiation is known, the outgoing shortwave radiation ($R_{s\uparrow}$) is simply the fraction reflected by the earth's surface. In absence of specific measurements of albedo, it is assumed that the earth's surface reflects 30% of the incoming shortwave radiation. Hence the outgoing shortwave radiation is estimated as

$$R_{s\uparrow} = -0.3 \times R_{s\downarrow} \quad (2)$$

One of the simplest methods of estimating the incoming longwave radiation ($R_{L\downarrow}$) from surface observations is [12, 13]

$$R_{L\downarrow} = c + (d \times \sigma \times T_a^4) \quad (3)$$

$c = -119 \text{ W m}^{-2}$

$d = 1.08$

T_a = air temperature

The outgoing longwave radiation ($R_{L\uparrow}$) is given by

$$R_{L\uparrow} = -\varepsilon \times \sigma \times T_g^4 \quad (4)$$

ε = land surface emissivity

σ = Stefan Boltzmann constant

T_g = land surface temperature

As per the sign convention, the incoming components are positive and the outgoing components are negative.

Finally, the net radiation (R_N) is the vector sum of the four components.

$$R_N = R_{s\downarrow} + R_{s\uparrow} + R_{L\downarrow} + R_{L\uparrow} \quad (5)$$

At Kaiga site, four Mini Boundary Layer Masts (MBLMs) have been installed for continuous measurements of meteorological parameters like wind speed, wind direction, air temperature, relative humidity, atmospheric pressure, rainfall and short and longwave radiation. Among the four components of net radiation, the shortwave radiation and incoming longwave radiation are measured at one location. The outgoing longwave radiation is measured at a different spatial location. These two stations are a few kilometres apart from each other, however they are located in similar type of soil condition. The four components are summed vectorially to derive the net radiation. These ground based measurements of net radiation for the corresponding time are used to assess the accuracy of satellite derived values. The shortwave radiation is measured using the Kipp and Zonen CMP series pyranometer which have a spectral range of 0.310 μm to 2.800 μm . Similarly, both the incoming and outgoing longwave radiation components are measured using the Kipp and Zonen CGR series pyrgeometer having a spectral range from 4.5 μm to 42 μm . For both, the satellite and ground based measurements, a surface albedo of 0.3 is assumed for the computation of the outgoing shortwave radiation from the incoming shortwave radiation.

3. Result and Discussion

Out of the 24 hours in a day, the data for four hours namely 5 (10.30 am), 8 (1.30 pm), 17 (10.30 pm) and 20 (01.30 am) GMT (IST) where both satellite and ground based measurements are present have been considered for comparison. The net radiation data are estimated from the components of short and longwave radiation. The accuracy of the net radiation depends on how well the individual components have been estimated. Hence in this study, as an example, the individual components namely the incoming shortwave radiation, incoming longwave radiation and outgoing longwave radiation are compared for the month of March 2013 for the times already mentioned. This comparison is shown in Figure 1 for (a) incoming shortwave radiation in the day time (10.30 am and 1.30 pm), (b) incoming longwave radiation in the day time (10.30 am and 1.30 pm), (c) incoming longwave radiation at night (10.30 pm and 01.30 am), (d) outgoing longwave radiation in the day time (10.30 am and 1.30 pm) and (e) outgoing longwave radiation at night (10.30 pm and 01.30 am) respectively. Since the outgoing shortwave radiation is just a fraction of the incoming radiation it is not compared separately. As seen from the Figure 1 (a), the satellite derived values of the short and longwave radiation compare well with the ground based measurements. For most of the times, the differences are within 10%. On certain days (for example 14th March, 2013) where significant differences are noticed between the satellite derived values and the ground based measurements, may be attributed to the presence of clouds which is neglected in this

study. This study assumes clear sky conditions for this site in the months of March, April, November and December. The agreement between the ground based measurements and satellite derived estimate points to the fact that this is a reasonable assumption for most of the times. From Figures 1 (b) to 1 (e) which compare the incoming / outgoing longwave radiation in the day and night time, it is seen that the satellite estimates match well with the ground based measurements. It is also emphasized that while the ground based observations refer to a point measurement, the satellite data are areally averaged retrievals. Several other sources of uncertainty in the satellite retrievals are assumptions used in the retrieval algorithm, non-uniform field of view of the sensor etc. The validity of the empirical equations used for the determination of net radiation also adds to the total uncertainty.

The Figures 2 (a) – 2 (d) compare the values of net radiation in the day and night time from MODIS and MBLM for the months of March, April, November and December 2013 respectively. The day time net radiation values are in the range of 0 – 600 W m^{-2} where as the night time values are in the range of 0 to -80 W m^{-2} . All the four figures indicate that the day time net radiation values are better estimated as compared to the night time values. This could be because of the fact that the daytime net radiation values are mainly governed by the incoming shortwave radiation which has less dependence on site characteristics. The night time net radiation values are governed by the incoming and outgoing longwave radiation, which are dependent on the site characteristics, and hence critically dependent on the retrieval algorithm used to derive these parameters from the satellite data. Finally, in Figure 3, the scatter plot of the average day and night time values from satellite and ground based measurements ($R^2=0.98$) is shown along with the best fit line (dotted curve). This plot reveals the comparison between the satellite and ground based measurements in spite of the various sources of uncertainty. To evaluate the performance of the MODIS derived net radiation values, several statistical indices like Mean Absolute Error (MAE), Root Mean Square Error (RMSE), Index of Agreement (IOA) and Correlation Coefficient (CORR) have been utilized [4, 7]. The MAE, RMSE, IOA and CORR values are given in Table – 1. From Table – 1, it is seen that the average differences (denoted by MAE) between MODIS derived net radiation and ground based measurement is $\sim 35 \text{ W m}^{-2}$ where as the average root mean square error is $\sim 50 \text{ W m}^{-2}$. These results are in good agreement with other studies in which MODIS has been used to obtain net radiation for a site [11]. Both the IOA and CORR indicate a good comparison between the satellite and ground based measurements. This study serves to validate the satellite derived values of net radiation using ground based measurements. Once validated, the satellite estimates can be used for the validation of atmospheric models for each grid instead of a comparison with a single ground measurement.

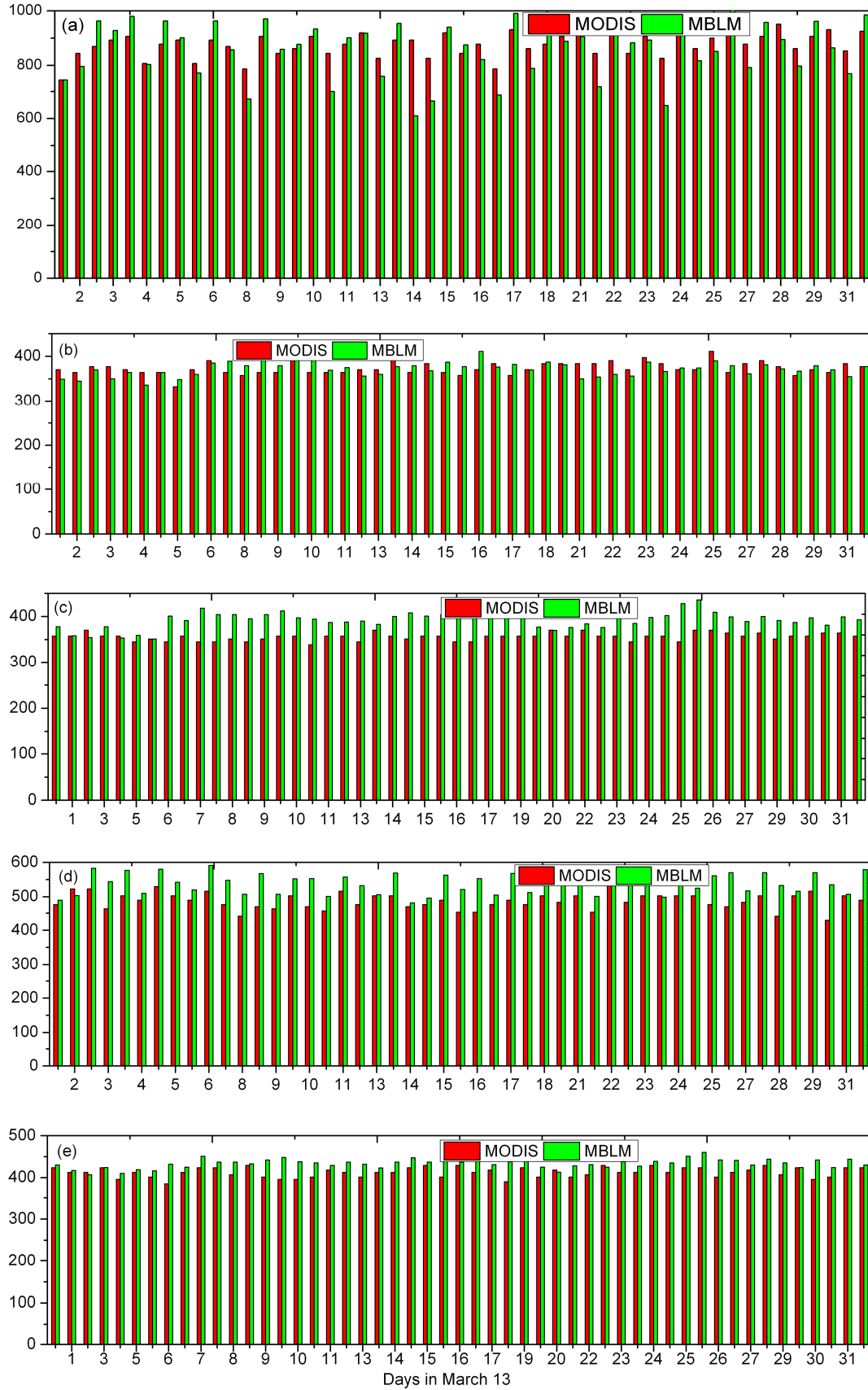


Figure 1. Comparison of individual radiation components derived from MODIS and MBLM for (a) incoming shortwave radiation in the day time (10.30 am and 1.30 pm), (b) incoming longwave radiation in the day time (10.30 am and 1.30 pm), (c) incoming longwave radiation at night (10.30 pm and 01.30 am), (d) outgoing longwave radiation in the day time (10.30 am and 1.30 pm) and (e) outgoing longwave radiation at night (10.30 pm and 01.30 am).

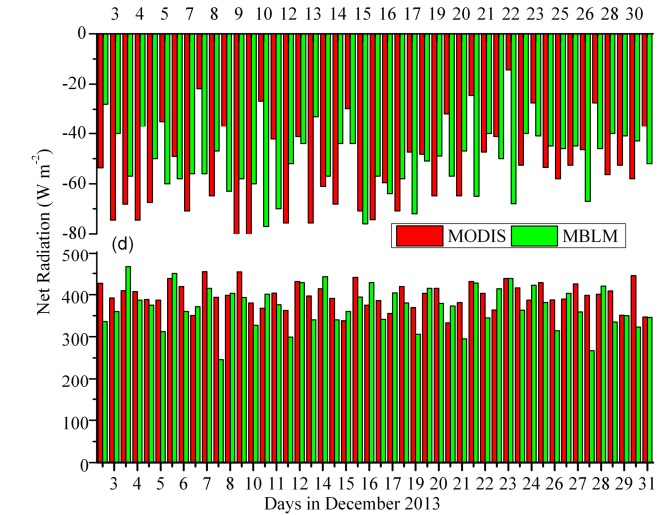
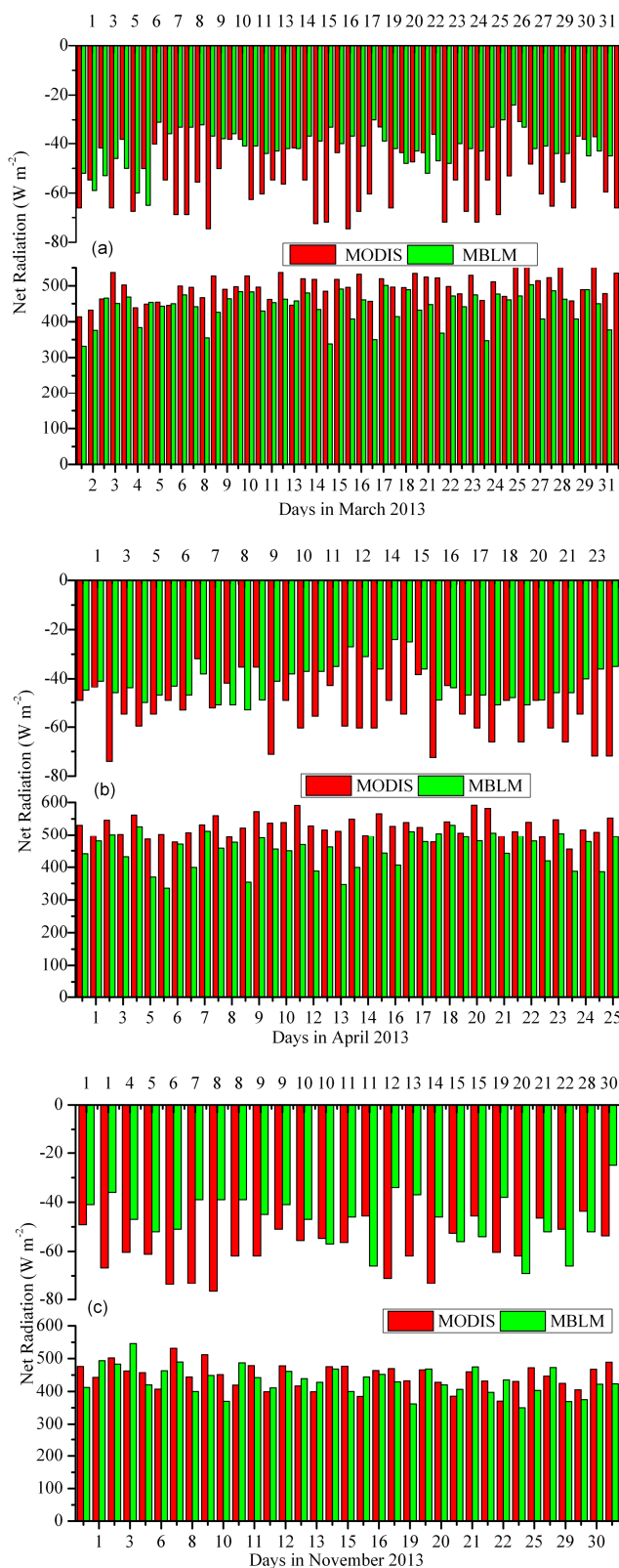


Figure 2. Net radiation values in the day (positive) and night time (negative) from MODIS and MBLM for (a) March, (b) April, (c) November and (d) December 2013.

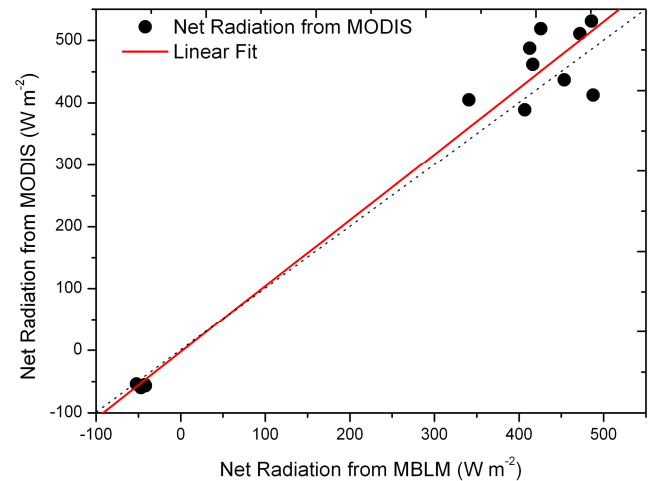


Figure 3. Scatter plot of average day and night net radiation values derived from MODIS and MBLM.

Table 1. Statistical Analysis.

	March	April	November	December
Average_MBLM (W m^{-2})	194	219	233	166
Average_MODIS (W m^{-2})	215	249	237	179
MAE (W m^{-2})	38	44	32	33
RMSE (W m^{-2})	53	63	39	44
IOA	0.98	0.98	0.99	0.99
CORR	0.99	0.99	0.98	0.98

AVG_MBLM – Average of ground based measurement, AVG_MODIS – Average of satellite, MAE – Mean Absolute Error, RMSE – Root Mean Square Error, IOA – Index of Agreement, CORR – Correlation Coefficient (Note: All statistical analysis are performed on co – located satellite and ground based data i.e. 5, 8, 17 and 20 GMT only)

4. Conclusions

This paper describes the development and application of the Satellite Estimate of Surface Energy Budget (SESEB) model in the estimation of net radiation from remotely sensed

data in clear sky conditions. The model results are validated using simultaneous ground based measurements for the months of March and April in 2013, representative of the warm season and the months of November and December in 2013, representative of the cold season. The day time net radiation values estimated from the satellite derived data compared well with the same obtained from ground based measurements. The night time values have relatively poor comparison with the ground based measurements owing to the greater sensitivity of the algorithm to the surface conditions. For the study duration of four months, a mean absolute error of 35 W m^{-2} and root mean square error of 50 W m^{-2} was observed between the satellite and ground based estimation of net radiation. The study suggests that the satellite data can be used to estimate the net radiation where ground based measurements are not available. They can also be used to validate the radiation algorithms in atmospheric models.

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