Indian Journal of Radio & Space Physics
Vol 44, March 2015, pp 51-55

A simple model for estimation of snow/ice surface temperature of Antarctic ice sheet using remotely sensed thermal band data

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Received 18 August 2014; revised received and accepted 22 January 2015

In this paper, a model has been developed to estimate surface temperature of Antarctic ice sheet using thermal bands of Moderate Resolution Imaging Spectroradiometer (MODIS) sensor images and in situ surface temperature measurements. The brightness temperature of snow/ice surface of Antarctica has been estimated for MODIS bands 31 and 32 using Planck's spectral radiation equation. Split window technique has been used to develop the model from brightness temperature and Automatic Weather Station recorded surface temperature. The model has been validated using *in situ* measurements of surface temperature of the ice sheet near Indian Antarctic Research Station 'Maitri'. High coefficient of determination (R2 in the range 0.952 - 0.99) and low root mean square error (0.8 - 1.2°C) has been obtained between modeled and *in situ* recorded surface temperature. The model is easy to use and can generate the surface temperature maps at spatial resolution of 1.0 km. These maps can be useful in various glaciological, hydrological, climatological and ecological studies of the ice sheet.

Keywords: Snow, Ice, Surface temperature, Antarctic ice sheet, Thermal bands, Satellite sensor images, Brightness temperature

PACS Nos: *92.40.vv*; *92.40.vw*; *92.60.hv*; 93.30.Ca

1 Introduction

Surface temperature is an important parameter for controlling various physical, biological and chemical processes on earth. It has been estimated for different land covers using various satellite sensors data by various researchers[1-8]. Generally, two types of methods are in vogue to estimate surface temperature using remote sensing data: (i) single infrared channel method and (ii) the split-window method. Single channel method requires radiative transfer model and vertical profiles of atmospheric data. The split-window method corrects for atmospheric effects based on differential absorption in adjacent infrared bands[2,9,10]. Studies have been devoted to establish the methodology for retrieval of land surface temperature (LST) from thermal bands of Moderate Resolution Imaging Spectroradiometer (MODIS), Advanced Very High Resolution Radiometer (AVHRR), Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) and many other satellites sensor data. LST can be retrieved using thermal infrared remote sensing only in clear sky conditions while microwave techniques have all weather capabilities[2]. Surface temperature estimated from thermal bands data of different multi-spectral satellite sensors has advantage of higher spatial resolution as compared to that estimated from passive microwave data. Thus, the intensity of emissions captured by thermal bands of multi-spectral images is stronger as compared to the intensity of emissions captured by passive microwave images. Passive microwave and thermal bands of multi-spectral images have been used to estimate surface temperature of various land covers. Key *et al.*[3] estimated clear sky surface temperature of polar regions using thermal bands data of AVHRR and Along Track Scanning Radiometer (ATSR) and obtained accuracies in the range of 0.3 - 2.1 K. Basist *et al.*[11] demonstrated the capability of Special Sensor Microwave Imager (SSM/I) to observe the land surface temperature in United States and the globe and reported an absolute error of about 2.0°C with *in situ* measurements. Hall *et al.*[6] produced daily surface temperature (IST) of sea ice at spatial resolution of 1 km and 4 km using Terra and Aqua MODIS images with root mean square error (RMSE) of 1.2 - 3.7 K. Brogioni *et al.*[7] estimated surface temperature of east Antarctic ice sheet using passive microwave remote sensing data of Advanced Microwave Scanning Radiometer-Earth (AMSR-E) with RMSE in the range 2 - 7 K. Negi *et al.*[12] derived a regression relation for estimation of snow surface temperature of snow cover in Western Himalayas using MODIS thermal bands data and ground data. The equation has been validated from *in situ* recorded data in lower, middle and upper Himalaya and an RMSE of 2.5°C was reported. In this paper, a simple model is presented to estimate surface temperature of the Antarctic ice sheet using only thermal bands data of the MODIS. The model generates surface temperature maps at spatial resolution of 1 km.

2 Study area and Data

The study area lies in the eastern Dronning Maud Land of East Antarctica. Indian research station Maitri is located in Schirmacher Oasis in the coastal margin of the Dronning Maud Land, East Antarctica at 70°45.94'S and 11°44.13'E (Refs 13,14). The study area considered in the present work extends from 70.2°S to 72°S and 8.6°E to 14°E (Fig. 1). It comprises ice shelves of Princess Astrid Coast, ice-free area of Schirmacher Oasis, continental ice sheet and Wohlthat Mountain from north to south. North of the Shirmacher Oasis is ice shelf spreading about 70 km up to Antarctic sea and south of the Oasis is continental ice sheet which increases in thickness towards south. Wohlthat Mountain is about 70 km south of the Shirmacher Oasis. The elevation ranges from 22 m near Antarctic sea to 3003 m on high Antarctic plateau in the study area. Most part of the study area is flat ice sheet having slope less than 5°. A small terrain with slope angle between 20° and 30° also exists near Schirmacher Oasis and Wohlthat Mountain.

In the present work, *in situ* recorded snow/ice surface temperature data and remotely acquired MODIS sensor data have been used. Snow and Avalanche Study Establishment (SASE) has installed two automatic weather stations (AWS) on Antarctic ice sheet at a distance of approximately 1 km and 8 km from Maitri research station. Infrared (IR) sensor mounted on these AWSs record hourly snow/ice surface temperature. Images from MODIS sensor on-board Terra and Aqua satellite (downloaded from http://ladsweb.nascom.nasa.gov) have been used for estimation of surface temperature. Channel 31 and 32 of MODIS sensor image are thermal bands and have been used to estimate brightness temperature. Salient specifications of MODIS data[15] is given in Table 1. MODIS sensor data on clear sky days for the period 2007 - 2012 have been collected for the study.

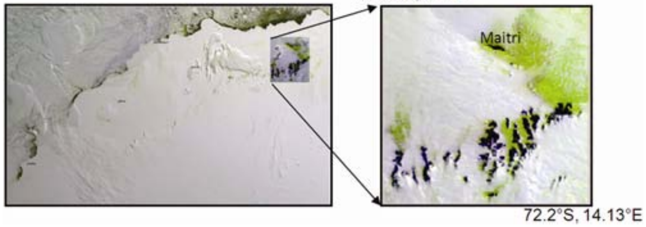

Fig. 1 — Study area in Antarctica

3 Methodology

The following form of equation within the framework of the split window algorithm[1,2,4,9] has been used for estimation of surface temperature in Antarctica.

$$T_s = a + b.T_{31} + c.(T_{31} - T_{32}) \quad \ldots(1)$$

where, T_s, is surface temperature; T_{31}, brightness temperature of MODIS band 31; T_{32}, brightness temperature of MODIS band 32; and a, b, c, regression coefficients. Emissivity of the snow/ice surface has been assumed to be unity in the present study[16]. Hori *et al.*[17] examined the dependence of the directional emissivity on various types of snow surfaces. They observed that emissivity at 10.5 and 12.5 μm for different snow types is different for nadir angle and off-nadir angle and vary from 0.949 to 0.997. They demonstrated that directional emissivity of snow in the thermal infrared vary depending upon the surface snow type. Emissivity of snow and ice also vary with melting of the snow/ice surface. Present study area has different types of snow/ice surfaces. As field observations are not available on different emissivity values of snow/ice surfaces and change in emissivity values

Table 1 — Salient specifications of MODIS sensor

Total number of bands	36
Wavelength range	0.4 – 14.4 μm
Swath	2330 km
Radiometric resolution	12 bit
Repeat cycle	1-2 days
Orbit elevation	705 km

Band	Spatial resolution, m	Spectral resolution, μm	Radiance_scale, mW cm^{-2} sr^{-1} μm^{-1}
Band 31	1000 x 1000	10.780 – 11.280	0.0000840022
Band 32	1000 x 1000	11.770 – 12.270	0.0000729698

due to melting of the snow/ice in the study area, it may have some inherent error in the model.

MODIS thermal bands 31 (10.780 - 11.280 µm) and 32 (11.770 - 12.270 µm) have been used to estimate brightness temperature in the study area. According to the black body radiation principle, the spectral radiance emitted from surface as a black body can be described by Planck's spectral radiation equation[18] given as:

$$L_\lambda (T) = 2\, h\, c^2 \lambda^{-5} (e^{hc/\lambda kT} - 1)^{-1} \quad \ldots(2)$$

where, L_λ, is spectral radiance of black body; h, Planck's constant (6.626×10^{-34} J s); c, velocity of light (3×10^{8} m s^{-1}); λ, wavelength; k, Boltzmann's constant (1.381×10^{-23} J K^{-1}); and T, brightness temperature.

Using Eq. (2), the brightness temperature can be estimated as[4]:

$$T = hc\lambda^{-1}k^{-1} [\log (1+2\, h\, c^2 \lambda^{-5} L_\lambda^{-1})]^{-1} \quad \ldots(3)$$

In Eq. (3), mean wavelength 11.03 and 12.02 µm for the MODIS bands 31 and 32 have been used, respectively for the estimation of brightness temperature. Spectral radiance (L_λ) values for MODIS bands 31 and 32 have been estimated using following equation[19]:

$$L_\lambda = \text{radiance\_scale}_\lambda\, (DN - \text{radiance\_offset}_\lambda) \quad \ldots(4)$$

where, radiance_scale$_\lambda$ and radiance_offset$_\lambda$ are the scale and offset parameters, respectively for MODIS spectral bands, radiance_scale$_\lambda$ for MODIS bands 31 and 32 are given in Table 1; radiance_offset$_\lambda$ for MODIS bands 31 and 32 are 1577.34 and 1658.22, respectively.

Spectral radiance for MODIS bands 31 and 32 have been estimated for different days of the years 2007, 2008 and 2009. Brightness temperature has been estimated for these days using Eq. (3). AWS recorded ***in situ*** surface temperature at the time of MODIS satellite pass and estimated brightness temperature have been used to obtain the values of constants a, b and c in Eq. (1). The coefficients obtained are given as:

$$a = -260.0967412,\ b = 0.959826974,\ \text{and}\ c = -1.034104696$$

These values of the coefficients a, b, and c have been used in Eq. (1) to estimate surface temperature at spatial scale and the model is given as:

$$T_s = -260.0967412 + 0.959826974 T_{31} - 1.034104696\, (T_{31} - T_{32}) \quad \ldots(5)$$

Using this model, surface temperature has been estimated at each pixel of the MODIS image in the study area. The algorithm was developed using the data of the years 2007, 2008, 2009 and the algorithm was validated at the AWS locations using data of different days of the years 2010 -2012.

4 Results and Discussion

Figures 2 and 3 show the MODIS derived surface temperature map of the study area on 12 January 2010 and 7 February 2012, respectively at 0900 hours. The surface temperature on 12 January 2010 varies from -19 to 6.9°C in the study area with mean value of -7.8±4.7°C. The surface temperature on 7 February 2012 varies from -25 to 4°C in the study area with mean value of -13.7±4.9°C. Surface temperature has been observed decreasing with time from January to February, which is obvious as the season changes from summer season towards winter season in the continent. Surface temperature has also been estimated for different days of the years 2007 - 2012 and surface temperature maps have been

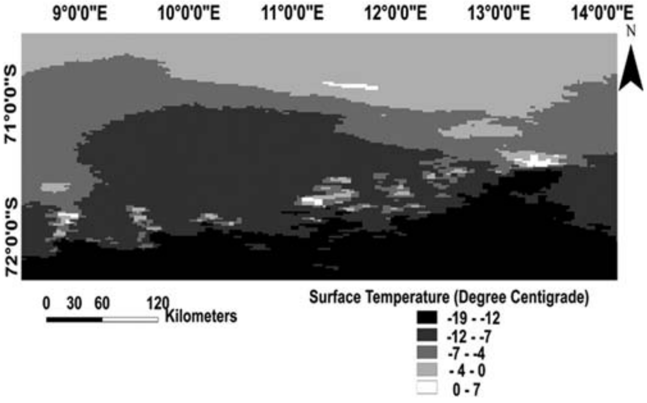

Fig. 2 — Surface temperature map of the study area for 12 January 2010 at 0900 hrs UT

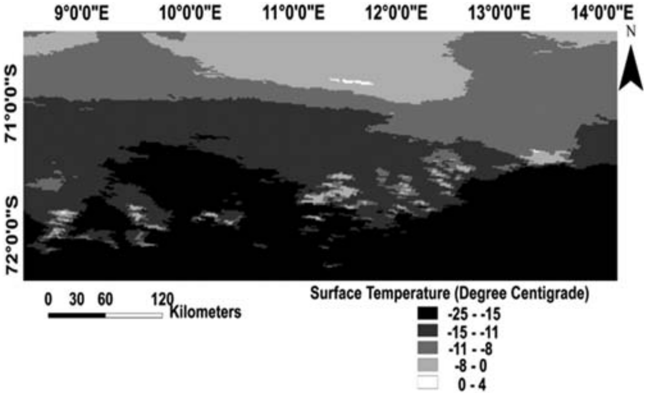

Fig. 3 — Surface temperature map of the study area for 7 February 2012 at 0900 hrs UT

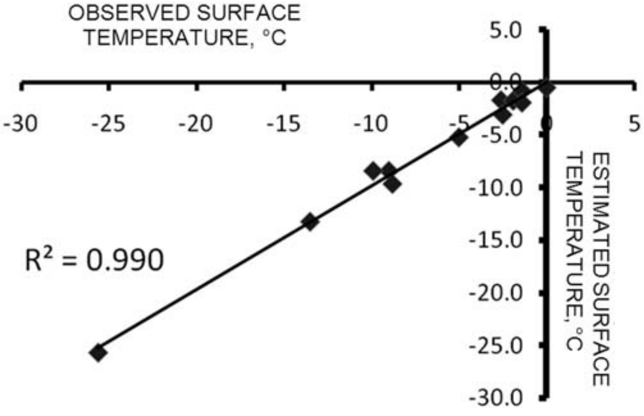

Fig. 4 — Observed vs estimated surface temperature for different clear sky days of the year 2010

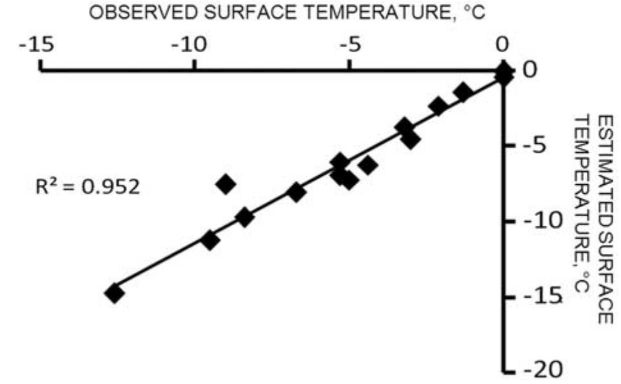

Fig. 5 — Observed vs estimated surface temperature for different clear sky days of the year 2011 and 2012

generated. These maps have been validated at the AWS locations using *in situ* recorded surface temperature values. The regression plot between estimated and observed surface temperature during different days of the year 2010 and 2011-12 are shown in Figs 4 and 5, respectively. High coefficient of determination (R^2 = 0.99 for 2010 and R^2 = 0.952 for summer season 2011-12) has been obtained between model estimated and *in situ* recorded values. Absolute error between observed and estimated surface temperature varied from 0.1°C to 1.5°C during different days of the year 2010, mean absolute error (MAE) obtained was 0.6°C and root mean square error (RMSE) obtained was 0.8°C. For the years 2011 and 2012, absolute error between observed and estimated surface temperature varied from 0°C to 2.2°C with MAE of 1.0°C and RMSE of 1.2°C, respectively.

The surface temperature maps, thus generated, may be used in various glaciological, ecological and environmental studies.

5 Conclusion

In the present study a simple algorithm has been developed to estimate snow/ice surface temperature of the Antarctic ice sheet using MODIS thermal bands data and *in situ* recorded data. Algorithm has potential to generate surface temperature maps from thermal bands images at spatial resolution of 1.0 km. These maps have been validated with ground observed values. A high coefficient of determination (R^2 = 0.952 to 0.99) and low root mean square error (RMSE = 0.8 - 1.2°C) has been obtained between model estimated and ground observed values. The maps may be potentially used for estimation of energy fluxes, hydrological, glaciological and other studies in Antarctica.

Acknowledgement

The authors are thankful to all the scientists/technical officers/technical staff of Snow and Avalanche Study Establishment (SASE), who participated in Indian Scientific Expedition to Antarctica and collected valuable data for the study. They acknowledge the logistic support provided by National Centre of Antarctic and Ocean Research (NCAOR), Goa, during field campaigns in Antarctica. NASA's LAADS web (http://ladsweb.nascom.nasa.gov) is duly acknowledged for providing MODIS data.

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