METEOROLOGICAL APPLICATIONS
Meteorol. Appl. **18**: 181–187 (2011)
Published online 16 August 2010 in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/met.221

An attempt for improving MODIS atmospheric temperature profiles products in clear sky

Majid Rahimzadegan and M. Reza Mobasheri*
Department of Remote Sensing Engineering, KN Toosi University of Technology, Tehran, Iran

ABSTRACT: Retrieving atmospheric temperature profile (TP) data through satellite thermal radiative measurement has gained lots of attentions in recent years. These retrieved profiles may involve some uncertainties. Although different methods have been introduced to minimize these uncertainties, they are time consuming and complicated. This work, based on the available methods, presents an approach for improving the clear sky TP calculation in two stages. In the first stage, a radiosonde mean TP is introduced to the radiation transfer equation and the deviation from this profile is calculated. In the second stage, by correcting the slope of this new profile and then using this new slope and land surface temperature, the improved TP for each pixel in the scene is calculated. A comparison between the model output TP and the one measured by radiosonde in steps of 100 m shows root mean square errors between 0.38 and 3.86 K. This shows considerable improvement compared to the Moderate Resolution Imaging Spectroradiometer (MODIS) products. Copyright © 2010 Royal Meteorological Society

KEY WORDS remote sensing; MODIS; thermal channels; temperature profile; atmosphere

Received 8 March 2010; Revised 18 May 2010; Accepted 23 June 2010

1. Introduction

The purpose of this work is to present a technique for decreasing the uncertainties involved with retrieving vertical profiles of the temperature in the atmosphere using five thermal channels of the Moderate Resolution Imaging Spectroradiometer (MODIS) in clear skies. Of course the MODIS is not a sounding instrument, but it does have many of the spectral bands necessary for sounding. These are similar to those of bands 1–6 of the High Resolution Infrared Radiation Sounder (HIRS) that is currently in service on the polar orbiting NOAA TIROS Operational Vertical Sounder (TOVS). Thus, it seems possible to calculate profiles of temperature and other parameters such as moisture, precipitable water vapour (Mobasheri *et al*., 2008), low fog and stratus clouds (Bendix *et al*., 2006), atmospheric aerosols (Péréa *et al*., 2009; Wang, 2010), ozone and atmospheric stability from MODIS infrared radiance measurements (Menzel *et al*., 2002). However, these parameters can be used as inputs in numerical models for weather nowcasting and forecasting, as well as for climatological models. This work is primarily based on the retrieval procedure used in the MODIS products, then a procedure is developed for those who seek a more precise temperature profile (TP) in the regions as small as a MODIS pixel.

In order to retrieve atmospheric TP through measurements of thermal emission, the emission of most abundant gases of known distribution must be used (Fleming and Smith 1971; Fritz *et al*., 1972; Rodgers, 1976; Twomey, 1977; Houghton *et al*., 1984). However, any uncertainties in this regard can create ambiguities in determination of TPs. These gases are carbon dioxide, with a relative volume abundance of 0.003 and oxygen with a relative volume abundance of 0.21 as a major constituent of the atmosphere (Fleming and Smith, 1971; Fritz *et al*., 1972; Rodgers, 1976; Twomey, 1977; Houghton *et al*., 1984).

In most cases these two gases satisfy the requirement of a uniform mixing ratio. In the case of carbon dioxide, the infrared vibrational-rotational bands and in the case of oxygen a microwave spin-rotational band can be used for this purpose (Fleming and Smith, 1971; Fritz *et al*., 1972). In most of the cases, finding a unique solution for the detailed vertical profile of temperature is unlikely because: (1) the emission emerges and initiates from relatively deep layers of the atmosphere (Mobasheri and Mobasheri, 2009); (2) the radiances observed within various spectral channels may come from overlapping layers of the atmosphere and consequently are not vertically independent (Fleming and Smith, 1971; Fritz *et al*., 1972), and, (3) some errors are involved with the measurements of outgoing radiance (Fleming and Smith, 1971; Fritz *et al*., 1972; Rodgers, 1976; Twomey, 1977; Houghton *et al*., 1984). As a result, various approaches differ both in the procedure in solving the sets of spectrally independent radiative transfer equations and in the type of ancillary data used to constrain the solution to ensure a meteorologically

* Correspondence to: M. Reza Mobasheri, Department of Remote Sensing Engineering, KN Toosi University of Technology, Mirdamad Cross, Tehran, Iran. E-mail: mobasheri@kntu.ac.ir

meaningful result (Fleming and Smith, 1971; Fritz *et al.*, 1972; Rodgers, 1976; Twomey, 1977; Houghton *et al.*, 1984).

The MODIS atmospheric profile retrieval algorithm is based on a statistical regression with the option for a subsequent non-linear physical retrieval of parameters such as temperature. The retrievals are valid if performed in a clear sky both in day and at night (http://daac.gsfc.nasa.gov/MODIS). The retrieval method that this work is based on is the work of Li *et al.* (2000), Hayden (1988) and Smith and Woolf (1988). In the MODIS atmospheric profiles retrieving algorithm a combination of 16 infrared spectral channels is used (Table I).

There are different methods for determination of TPs from satellite sounding measurements. These methods usually use the previously determined statistical relationships between measured (or modelled) radiances and the corresponding atmospheric profiles. The output of these methods is used as a first-guess for a physical retrieval algorithm (e.g. International TOVS Processing Package). Based on the work of Seemann *et al.* (2006), in a cloud free sky, the radiation arriving at the top of the atmosphere at frequency f_j can be considered as the sum of the radiance contributed from the Earth's surface and those contributing from all levels in the atmosphere:

$$L(fj) = \sum_{i=1}^{N} P[f_j, T(p_i)] w(f_j, p_i) \quad j = 1, 2, \ldots, M \tag{1}$$

where $w(f_j, p_i)$ is a weighting function to account for the weight of contribution of each level, $P[f_j, T(p_i)]$ is the Planck flux density at frequency f_j and temperature T at pressure level p_i where the dependence of the pressure to the height is presumed. The weighting function combines the effects of emissivity ε and transmissivity τ of the atmosphere up to the level i in band j and can be shown by the following equation Seemann *et al.* (2006):

$$w(f_j, p_i) = \varepsilon(f_j, p_i)\tau(f_j, 0 \longrightarrow p_i) \tag{2}$$

The objective is to determine the temperature at N levels in the atmosphere from M radiance observations. However, because the M radiance observations are not independent, there is no unique solution to Equation (1). A solution to this problem was introduced by Seemann *et al.* (2006) in which the deviation from a predefined profile was calculated:

$$L(f_i) - L_0(f_j) = \sum_{i=1}^{N} \left\{ P\left[f_j, T(p_i)\right] - P\left[f_j, T_0(p_i)\right] \right\} w(f_j, p_i) + e(f_j) \tag{3}$$

where $e(f_j)$ is the error in the radiance observations. Assuming linear behaviour of the Planck function with frequency in the thermal region of the spectrum Mobasheri (2006), one can invert Equation (3) to find TP as (based on the work of Seemann *et al.*, 2006):

$$T(p_i) - T_0(p_i) = \sum_{j=1}^{M} A\left(f_j, p_i\right)\left[L(f_i) - L_0(f_j)\right] \tag{4}$$

or in a matrix form:

$$T = AR \tag{5a}$$

where A is a linear operator containing the effects of weighing function as well as the transmissivity of the atmosphere for the spectral bands used. A is a matrix converting the matrix of radiance R to TP. If the intention is to determine the temperature at m levels using radiance of n thermal bands, then:

$$\begin{bmatrix} T1 \\ T2 \\ . \\ . \\ Tm \end{bmatrix} = \begin{bmatrix} a11 & a12 & \cdots & a1n \\ a21 & a22 & \cdots & a2n \\ \ldots\ldots & & & \\ am1 & am2 & \cdots & amn \end{bmatrix} = \begin{bmatrix} R1 \\ R2 \\ . \\ Rn \end{bmatrix} \tag{5b}$$

This means that the temperature at level i can be calculated using radiances received by n thermal bands as follows:

$$T_i = a_{i1}\ R_1 + a_{i2}\ R_2 + \cdots + a_{in}\ R_n \tag{5c}$$

If one can provide temperature profiles T_0 and T from time and space co-located radiosonde data and their corresponding radiances of L_0 and L from satellite (or balloon) measurements, the operator matrix A can be calculated. Of course this matrix may differ from one geographical region to another. It is worth noting that such an approach would not involve any radiative

Table I. MODIS thermal spectral band specifications.

Primary atmospheric application	Band	Bandwidth (μm)
Surface/cloud temperature	20	3.660–3.840
	21	3.929–3.989
	22	3.929–3.989
	23	4.020–4.080
Atmospheric temperature	24	4.433–4.498
Temperature profile	25	4.482–4.549
Moisture profile	27	6.535–6.895
	28	7.175–7.475
	29	8.400–8.700
Ozone	30	9.580–9.880
Surface temperature	31	10.780–11.280
	32	11.770–12.270
Temperature profile	33	13.185–13.485
	34	13.485–13.785
	35	13.785–14.085
	36	14.085–14.385

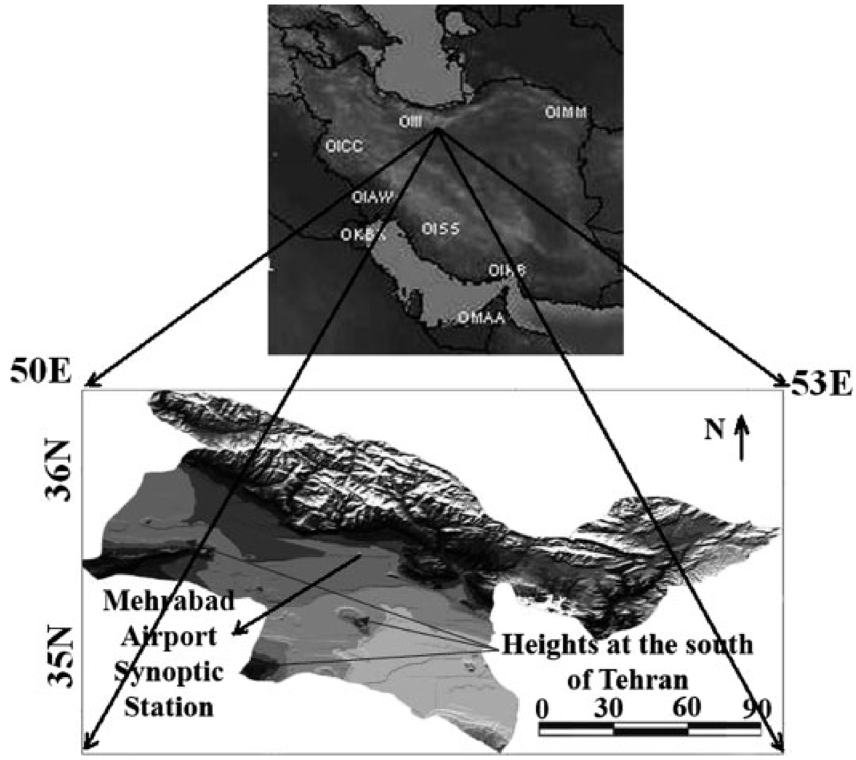

Figure 1. A DEM of the Mehrabad synoptic station region located at south of Tehran capital city in the southern slopes of Alborz Mountains. White codes are for those stations where radiosondes collect data on a routine basis (Mobasheri *et al*., 2008).

transfer calculations and this is actually the purpose of this research.

2. Methodology

2.1. Site and data selection

Temperature, pressure and dew points are parameters that are collected by radiosonde sensors and transmitted directly to the surface. A relatively complete bank of radiosonde data are accessible from the Wyoming University site as well as the Iran Meteorological Organization. These data are collected on a routine basis twice a day (0000 UTC and 1200 UTC). The selected site for this work was Mehrabad Airport synoptic station located in the southern part of Tehran, capital city of Iran (Figure 1). This station is located at 51°, 21′E and 35°, 41′N at an altitude of 1191 m. The index of this station is OIII and its number is 40 754.

MODIS images are only available from 1999. To select proper data, cloud-free MODIS images were first selected, with radiosonde data as close as possible to the satellite acquisition time. To carry out weather analysis for the time of study, the thermodynamic graphs such as *Stuve* or *Skew-T* were used. In these graphs, temperature, pressure and dew point profiles as well as condensation temperature and pressure were analysed. This helped extraction of information regarding atmospheric stability as well as the possibility of the presence of small patches of clouds that otherwise cannot be detected in the low resolution MODIS images. The presence of small patches of clouds within a pixel increases the uncertainty of satellite TPW assessment (Jeffery and Austin, 2003).

2.2. Temperature profile preparation

The methodology of this work can be explained in six steps as follows.

Step 1. Seven MODIS/Terra images in Production Data Set (PDS) format were supplied (http://eoweb.dlr.de:8080/short_guide/D-MODIS.html). This format is the expected input format for the International MODIS/AIRS Processing Package (IMAPP). Three of these images were used for modelling and the other four for model evaluation. The tasks of unpacking, geolocation and calibration were carried out using IMAPP software. This software allows users of TERA/AQUA Level-0 data to produce calibrated and geolocated MODIS radiances (Level-1 data). The software was developed at NASA and modified by the University of Wisconsin (http://cimss.ssec.wisc.edu/~gumley/IMAPP/IMAPP.html) and runs on various UNIX platforms. The output at this stage was a Level 1B image.

Step 2. Using Scan Magic software (the ScanMagic software is a stand-alone Windows-based application, for processing remote sensing data (http://www.scanex.ru/en/software/default.asp?submenu=scanmagic&id=index)) the geometrical corrections based on a Lambertian system with an elliptical base of WGS84 (Defense Mapping Agency, 1987) were carried out by applying the nearest neighbourhood method. A subset of 74 by

102 pixels for the region of study was then cut as a sub-image. The reason for this selection was the homogeneity of the surface cover in this area.

Step 3. A cloudiness test was carried out using MOD35 (Ackerman *et al*., 1998) and cloud free pixels with more than 95% confidence were selected. To carry out this test a product of Total Precipitable Water (TPW) was needed. This TPW was produced using an adjusted method presented by Mobasheri *et al*. (2008) for the same region of study.

Step 4. To prepare a TP as an initial guess for the algorithm, a 5 year (2004–2008) radiosonde data set consisting of 140 TPs all for the times of satellite overpass in June was averaged (T_{mean}).

Step 5. Using three MODIS images, from 8 June 2004, 15 June and 22 June 2007 and the corresponding TPs of the radiosonde and Equations (5b) and (5c), the following sets of independent equations were solved for A_1, A_2 and A_3:

$$T_j - T_i = A_i(R_j - R_i),\ i, j = 1, 2, 3 \text{ and } i \neq j \quad (6)$$

where temperature T was retrieved from radiosonde and radiances R was calculated from corresponding MODIS thermal channels. The mean of these $A's$ (A_{mean}) was then calculated by averaging A_1, A_2, and A_3.

Step 6. To calculate a mean value for radiance (R_{mean}), a new TP, T_4 (from radiosonde and interpolated in the height steps of 100 m) and the corresponding radiance of R_4 (from MODIS 8 June 2007) along with the calculated A_{mean} and T_{mean} (interpolated in the height steps of 100 m) were used (Equation (7)):

$$R_{mean} = R_4 + (T_{mean} - T_4)/A_{mean} \quad (7)$$

Using T_{mean}, R_{mean} and A_{mean} along with any calculated R_x from a MODIS image, one can now calculate the temperature profile T_x (in the height steps of 100 m) for every pixel in the scene. A sample A_{mean} matrix consists of 5 columns and 108 rows and is shown in Figure 2.

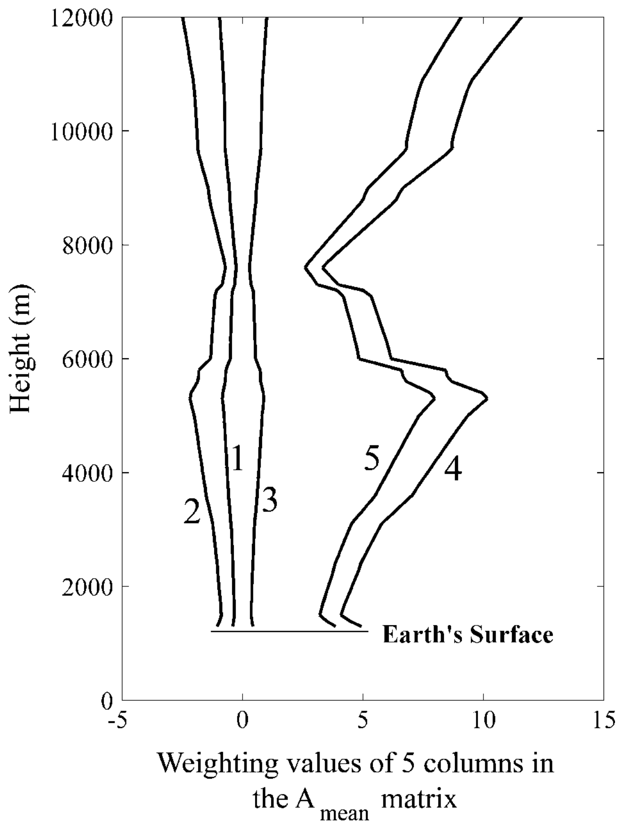

Figure 2. Variation of five column of matrix A_{mean} matrix with height.

3. Results and analysis

This method was applied to four MODIS scenes of 2 June, 5 June, 11 June and 21 June 2007. The calculated TPs were then compared to those extracted from radiosonde data for the time of satellite overpassing. The results are shown in Figure 3. As can be seen, there is a high agreement between the predicted and measured profiles. The calculated root mean square error (RMSE) for each one of these calculated profiles (interpolated in steps of 100 m) is shown in Table II.

Although the model's outputs show acceptable agreement with those of measured by radiosonde there might be some way to decrease RMSE between model output and radiosonde measured TP. To investigate this, the following technique was applied.

1. The slope of TPs measured by radiosonde at each height and those predicted by the model (in step 5) at the same heights were calculated.
2. Using Equations (8a) and (8b), the height weighed mean value of these slopes was then calculated:

$$\text{Radiosonde Mean Slope} = \frac{1}{H}\int_0^H S_R(z) \times dz \quad (8a)$$

$$\text{Model Predicted Mean Slope} = \frac{1}{H}\int_0^H S_M(z) \times dz \quad (8b)$$

Here, $S_R(z)$ is height dependent slopes of radiosonde measured TP, $S_M(z)$ is model-retrieved temperature slope profiles and H is the scale height. The ratio of Equations (8a) to (8b) was found to be 0.96.

3. To correct the MODIS calculated slope to read those which were measured by radiosonde the following equation is used:

$$\text{Radiosonde Equivalent Slope (RES)} = 0.96 \times \text{MODIS Calculated Slope (MCS)} \quad (9)$$

4. Using land surface temperature retrieved by MODIS and the calculated RES, one can calculate the temperature at 100 m. This temperature will be used in the

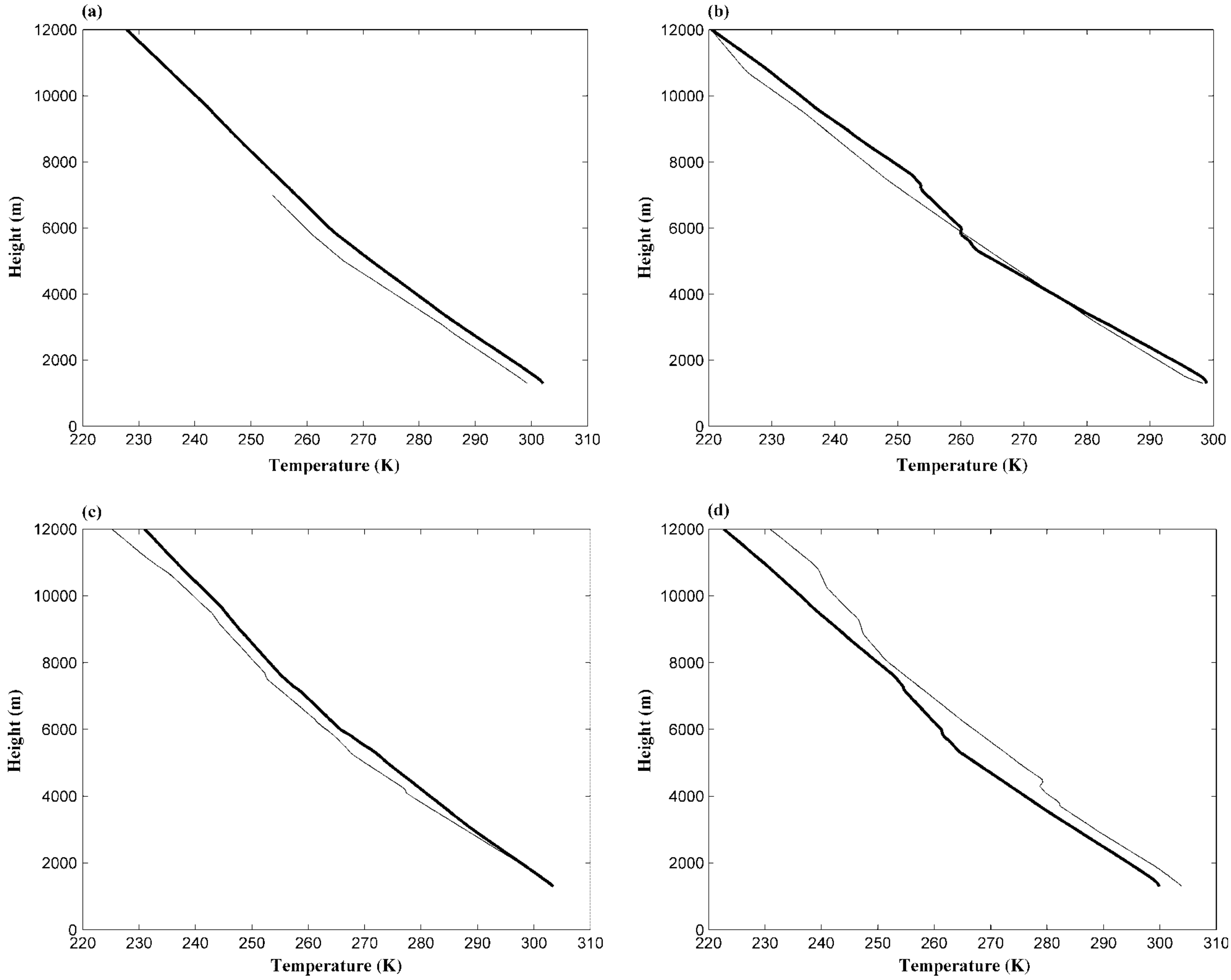

Figure 3. Retrieved (thick line) and measured (thin line) TP for (a) 2 June 2007, (b) 5 June 2007, (c) 11 June 2007 and (d) 21 June 2007.

next step to calculate the temperature at 200 m and so on.

This procedure can continue until the whole profile is calculated. This was done for the four profiles and the results are shown in Figure 4.

The RMSE between measured and calculated TPs after the slope correction shows considerable improvements in retrieving TP (Table II).

Table II. The results of calculated RMSE between measured (radiosonde) and MODIS (second column), model retrieved temperature profiles before (third column) and after (last column) slope corrections.

Image acquisition date	RMSE (K) MOD07 products	RMSE (K) model output before slope correction	RMSE (K) model output after slope correction
2 June 2007	7.21	4.04	0.38
5 June 2007	6.79	2.72	1.73
11 June 2007	6.21	3.44	1.32
21 June 2007	8.41	5.41	3.86

4. Conclusions

Solving the radiation transfer equation for every pixel is very time consuming, even if it is not uncertain most of the time. This work presents a simplified method in two stages. In the first stage, a mean TP is introduced to the radiation transfer equation and the deviation from this profile was calculated. In the second stage by correcting the slope of this new profile by applying Equation (9) and then using this new slope and land surface temperature, the TP for each pixel can be calculated. A minimum mean RMSE of 0.38 K was found for the profile compared to the radiosonde measurements where it shows considerable improvement compared to previous values of 1 K claimed by Seemann *et al.* (2003) and 0.9 K by da Costa *et al.* (2008). Of course, for the upper range of RMSE values, the present method gives 3.86 K, while this is 3 K for Seemann *et al.* (2003) and 2.7 K for da Costa *et al.* (2008). It is believed that this discrepancy comes from the interpolation of radiosonde temperature data carried out in this work and can be improved if one could decrease the height step size of the radiosonde measurements.

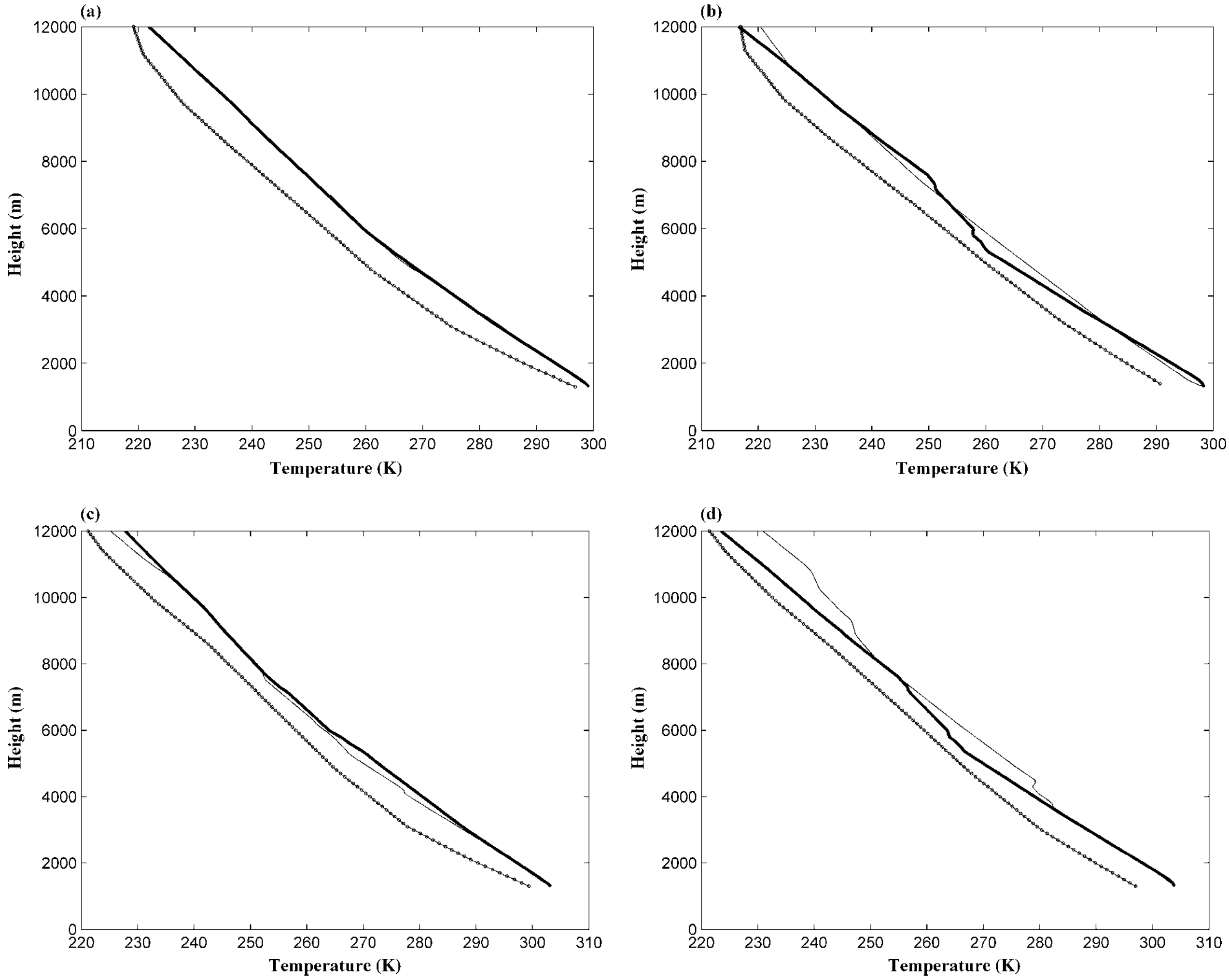

Figure 4. MODIS product (dashed line) radiosonde measured (thin line), and retrieved temperature profile (thick line) after slope correction for (a) 2 June 2007, (b) 5 June 2007, (c) 11 June 2007 and (d) 21 June 2007.

References

Ackerman SA, Strabala KI, Menzel WP, Frey RA, Moeller CC, Umley LE. 1998. Discriminating clear sky from clouds with MODIS. *Journal of Geophysical Research* **103**: 32141–32157.

Bendix J, Thies B, Nauß T, Cermak J. 2006. A feasibility study of daytime fog and low stratus detection with TERRA/AQUA-MODIS over land. *Meteorological Applications* **13**: 111–125.

da Costa SS, Rodrigues JV, Gonçalves WA, de Souza RAF. 2008. Performance of sounding retrievals from AIRS, GOES10, MODIS and HIRS Radiances during Mini-Barca campaign. *Anais XIV Simpósio Brasileiro de Sensoriamento Remoto*, Natal, Brasil, 25–30 Abril 2009. INPE: Natal, Brazil; http://marte.dpi.inpe.br/col/dpi.inpe.br/sbsr@80/2008/11.17.22.19/doc/1647-1652.pdf 1647–1652.

Defense Mapping Agency. 1987. World Geodetic System 1984, its definition and relationships with local geodetic systems. DMA Technical Report 8350.2, Department of Defense USA ftp://164.214.2.65/pub/gig/tr8350.2/wgs84fin.pdf.

Fleming HE, Smith WL. 1971. Inversion techniques for remote sensing of atmospheric temperature profiles. Reprint from Fifth Symposium on Temperature. *Instrument Society of America* **22**: 39–50.

Fritz S, Wark DQ, Fleming HE, Smith WL, Jacobowitz H, Hilleary DT, Alishouse JC. 1972. Temperature sounding from satellites. NOAA Technical Report NESS 59. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Environmental Satellite Service: Washington, DC; 49.

Hayden CM. 1988. GOES-VAS simultaneous temperature-moisture retrieval algorithm. *Journal of Applied Meteorology* **27**: 705–733.

Houghton JT, Taylor FW, Rodgers CD. 1984. *Remote Sounding of Atmospheres*. Cambridge University Press: Cambridge, United Kingdom; 1–343.

Jeffery CA, Austin PH. 2003. Unified treatment of thermodynamic and optical variability in a simple model of unresolved low clouds. *Journal of the Atmospheric Sciences* **60**: 1621–1631.

Li J, Wolf W, Menzel WP, Zhang W, Huang HL, Achtor TH. 2000. Global soundings of the atmosphere from ATOVS measurements: The algorithm and validation. *Journal of Applied Meteorology* **39**: 1248–1268.

Menzel WP, Seemann SW, Li J, Gumley LE. 2002. *MODIS Atmospheric Profile Retrieval Algorithm Theoretical Basis Document*. University of Wisconsin-Madison: Madison, WI.

Mobasheri MR. 2006. *Fundamental of Physics in Remote Sensing and Satellite Technology*, Farsi (ed.). K.N.Toosi University of Technology Publication: Tehran, Iran; 23–102.

Mobasheri MR, Mobasheri A. 2009. Analytical investigation of radiation flux in the water surface skin with application to the remote sensing of SST. *Journal of Oceanography* (in Farsi) **1**: 33–44.

Mobasheri MR, Purbagher Kordi SM, Farajzadeh M, Sadeghi Naeini A. 2008. Improvement of remote sensing techniques in TPW assessment using radiosonde data. *Journal of Applied Sciences* **8**(3): 480–488.

Péréa JC, Pont V, Mallet M, Bessagneta B. 2009. Mapping of PM10 surface concentrations derived from satellite observations of aerosol optical thickness over South-Eastern France. *Atmospheric Research* **91**: 1–8.

Rodgers CD. 1976. Retrieval of atmospheric temperature and composition from remote measurements of thermal radiation. *Reviews of Geophysics and Space Physics* **14**: 609–624.

Seemann SW, Borbas EE, Li J, Menzel WP, Gumley LE. 2006. Modis Atmospheric Profile Retrieval Algorithm Theoretical Basis Document. MOD07/MYD07 ATBD C005, Version 6.

Seemann SW, Li J, Menzel WP, Gumley LE. 2003. Operational retrieval of atmospheric temperature, moisture, and ozone from MODIS infrared radiances. *Journal of Applied Meteorology* **42**: 1072–1091.

Smith WL, Woolf HM. 1988. A Linear simultaneous solution for temperature and absorbing constituent profiles from radiance spectra. *Technical Proceedings of the Fourth International TOVS Study Conference* Igls, Austria.

Twomey S. 1977. *An Introduction to the Mathematics of Inversion in Remote Sensing and Indirect Measurements*. Elsevier: New York, NY.

Wang KY. 2010. Profiles of the atmospheric temperature response to the Saharan dust outbreaks derived from FORMOSAT-3/COSMIC and OMI AI. *Atmospheric Research* **96**: 110–121.