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Evaluation of Terra/MODIS atmospheric profiles product (MOD07) over the Iberian Peninsula: a comparison with radiosonde stations

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Remote sensing techniques are a useful tool for continuous observation of the Earth at global scale. However, products derived from remote sensing data require a rigorous validation using in situ data. Moderate Resolution Imaging Spectroradiometer (MODIS) is not really a sounding instrument, but it does have 16 infrared bands (bands 20–36 covering the spectral range from 3 µm to 14 µm) that allow the retrieval of temperature and moisture profiles as well as total column integrated magnitudes. In this paper we show the results obtained in the evaluation of MOD07 daytime and nighttime products over the Iberian Peninsula during the decade from 2000 to 2010 using nine radiosonde stations. Although MODIS limitations in comparison with other sounding instruments, the validation provided satisfactory results, with bias (MOD07 minus radiosonde) < 0.3 cm and a standard deviation of 0.5 cm for the total column water vapor, and bias around 1 K on average with standard deviations between 2 K and 3 K for air temperature at different pressure levels. On average, bias was positive and below 2 K with standard deviations around 5 K for the dew point temperature case. Large errors were found in this case for pressure levels higher than 50 hPa.

Keywords: MODIS; MOD07; atmospheric profiles; water vapor; air temperature; dew point temperature

1. Introduction

The atmosphere is one of the major system components of the Earth. Global climate and weather modeling requires accurate monitoring of atmospheric parameters such as air temperature and moisture or total column precipitable water vapor (WV). The analysis of anomalies and trends in these parameters has received an increasing attention because of the reported global warming through the Intergovernmental Panel on Climate Change studies. Therefore, continuous monitoring of atmospheric parameters at global scale is a key issue in order to assess changes in our climate.

Traditionally, the atmosphere has been characterized by sparse in situ measurements of near-surface parameters (e.g. air temperature and relative humidity measured in meteorological stations) or total column parameters (e.g. total column precipitable WV). The vertical structure of the atmosphere has been also characterized by sparse in situ measurements based on the launching of radiosonde data over particular sites and typically at 00 and 12 UTC. In this current digital era, remote sensing techniques for Earth Observation are a unique tool to overcome these problems, since they allow a

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global coverage and provide measurements at different temporal and spatial scales. In the case of the atmosphere observation, different infrared soundings have been used in the past or are currently used to extract vertical profiles of temperature and moisture at global scale, with spatial resolution ranging approximately from 10 km to 50 km. However, the main advantage of the Moderate Resolution Imaging Spectroradiometer (MODIS) for retrieving the distribution of atmospheric temperature and moisture is its high spatial resolution (5 km). This increased spatial resolution delineates horizontal gradients of moisture, temperature, and atmospheric total ozone better than other instruments (Seemann et al. 2003). Therefore, MODIS atmospheric products, in particular the atmospheric profiles product – MOD07, are suitable not only for global studies but also for studies at regional scales. Other useful application of global vertical profiles is related to the atmospheric correction of remote sensing data in order to retrieve different bio-geophysical parameters from the surface, such as reflectance and emissivity spectra, land surface temperature, etc. For instance, this option was explored in Jiménez-Muñoz et al. (2010), showing the potential of MOD07 data to atmospherically correct high resolution remote sensing data acquired by Thematic Mapper on board Landsat 5 or Advanced Spaceborne Thermal Emission and Reflection Radiometer on board Terra, as well as low resolution data such as MODIS (Hulley and Hook 2011) or Spinning Enhanced Visible and Infrared Imager (Jiménez-Muñoz et al. 2014).

Different validation exercises have been performed to assess the accuracy of MOD07 products, for example using ARM CART sites and by intercomparison with other sounding instruments derived products (Seemann et al. 2003, 2008). In this paper we assess the accuracy of MOD07 product through a long-term validation (2000–2010) over the Iberian Peninsula using radiosonde data at different stations. We are particularly interested on performance of MOD07 products for atmospheric correction of optical remote sensing data purposes, so no homogenization procedures were applied to the long-term series, as required for trend analysis. Therefore, the validation is performed by direct comparison between the parameters extracted from daily MOD07 products (with no further data manipulation, as will be used in the case of atmospheric correction of a particular image) and the same parameter measured by the radiosonde data at similar MOD07 acquisition time.

2. Data description and processing

2.1. MODIS atmospheric profiles product (MOD07)

MODIS project provides the scientific community with many standard products, the atmospheric profiles product among them, denoted as MOD07 or MYD07 when the Terra or Aqua platform is used, respectively. In this paper Terra products (MOD07) were used. MOD07 consists of several parameters, such as total-ozone burden, atmospheric stability, temperature and moisture profiles, and atmospheric WV. All of these parameters are produced day and night at 5 × 5 1-km pixel resolution when at least nine observations are cloud free. It provides a total amount of 20 atmospheric levels. In particular, the pressure levels of profiles are 5, 10, 20, 30, 50, 70, 100, 150, 200, 250, 300, 400, 500, 620, 700, 780, 850, 920, 950, and 1000 hPa.

MOD07 product is generated from an algorithm for retrieving vertical profiles of atmospheric temperature and moisture from multi-wavelength thermal radiation measurements in clear skies. While MODIS is not a sounding instrument, it does have many of the spectral bands found in other sounding instruments, so it is possible to generate profiles of temperature and moisture as well as total column estimates of precipitable WV, ozone, and atmospheric stability from its infrared radiance measurements. Basically, the algorithm is a statistical regression with the option for a subsequent non-linear physical retrieval. It is not the scope of this paper to focus on the algorithm retrieval. The reader can found a detailed description in Seemann et al. (2003, 2008), and also in the Algorithm Theoretical Basis Documents (available at http://modis.gsfc.nasa.gov/data/atbd/atmos_atbd.php) and MODIS Atmosphere Web site at http://modis-atmos.gsfc.nasa.gov/. In this paper we analyzed MOD07 version 5, although a new version (v6) is recently available.

MOD07 products over the Iberian Peninsula were downloaded in Hierarchical Data Format from the MODIS web page covering the period between years 2000 and 2010 and including daily products both at day and night. 5728 daytime images and 5826 nighttime images were downloaded and processed. Daytime imagery was acquired mainly in the time period 1000–1300 UTC, whereas nighttime imagery was acquired in the time period 2100–2330 UTC.

Although the analysis was performed at daily level over particular pixels (located at the radiosonde stations), a complete imagery processing was also performed for visualization purposes. This processing included the geometric correction of each MOD07 product, the co-location into the same grid (covering the Iberian Peninsula) to assure a perfect overlapping between the different images, and also the generation of monthly means both at day and night. As an illustrative example, Figure 1b–f display some of the MOD07 parameters (monthly values of surface temperature, air temperature, and atmospheric WV) over the Iberian Peninsula for July 2010.

2.2. Atmospheric soundings

Vertical profiles extracted from nine radiosonde stations located in the Iberian Peninsula were used to validate the MOD07 product (Table 1; Figure 1a). These radiosonde stations are operated by the national meteorological services (Agencia Estatal de Meteorología – AEMET in Spain, Instituto Português do Mar e da Atmosfera in Portugal, and Met Office in UK), and they were downloaded from the free available web site at the University of Wyoming: http://weather.uwyo.edu/upperair/sounding.html. Measurements included in these vertical profiles are atmospheric pressure, geopotential height, air temperature, dew point temperature, relative humidity, mixing ratio, and precipitable water. Total precipitable WV content is also provided by integration of the mixing ratio (Ross and Elliot, 1996). The time period considered in this paper covers from 1 January 2000 to 31 December 2010 at two different times of the day, 00 and 12 UTC.

2.3. Validation strategy

Values of air temperature and dew point temperature were extracted from one-single MOD07 pixel centered at the latitude and longitude of the radiosonde stations (Table 1) for the 20 nominal pressure levels. For a direct comparison between MOD07 and radiosonde data, the latter values were interpolated to the MOD07 pressure levels in order to perform the validation. The interpolation was carried out using a single segmentation spline method (Jiménez-Muñoz et al. 2010). The last pressure level (5 hPa) included a huge amount of nonvalid data, so this level was not considered in this analysis. Similarly total precipitable WV values extracted from the MOD07 were compared to the ones provided by the radionsonde. Only MOD07 products acquired between 1100 and 1300

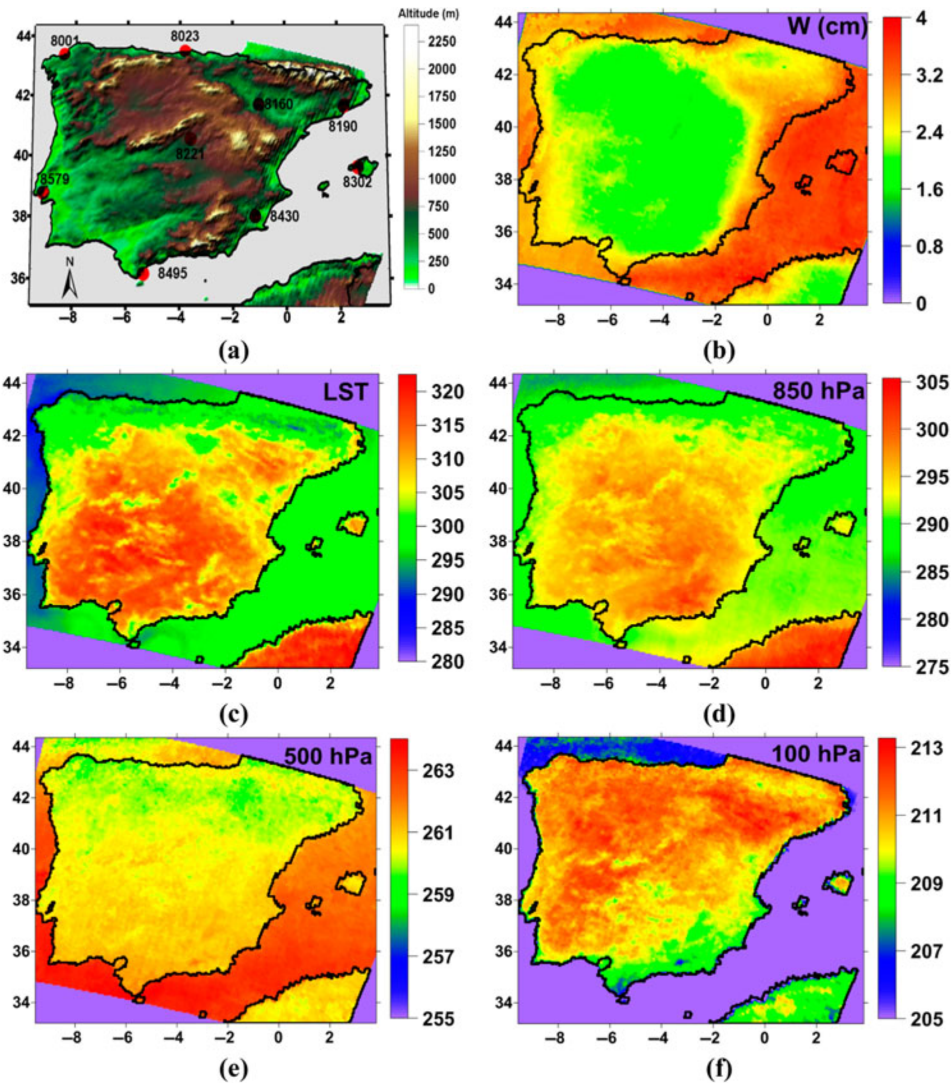

Figure 1. (a) Study area and radiosonde stations used in the validation. They marked over a Digital Elevation Model and identified with an ID number (see Table 1). Examples of maps of monthly values (July 2010) generated from MOD07 products are also given; (b) total atmospheric WV; (c) land surface temperature (LST); (d) air temperature at 850 hPa; (e) air temperature at 500 hPa, and (f) air temperature at 100 hPa.

UTC and between 2300 and 0000 UTC were compared to radiosondes launched at 1200 and 0000 UTC, respectively. Differences in MOD07 acquisition time and radiosonde launching time could in theory influence the validation, but reduction of the MOD07 time period considered in the comparison (only products near 1200 UTC and 0000 UTC) did not provide better results. Outliers were filtered using the criteria $\langle x \rangle \pm 3\sigma$ (where $\langle x \rangle$ is the mean value and σ the standard deviation), following the criterion employed by Mattar et al. (2011). It should be noted that only a small amount of nighttime data are valid in

Table 1. Meteorological stations located in the Iberian Peninsula and used in the validation.

St. ID	St. name	Country	Lat. (*N*)	Lon. (E)	Elev. (m)	Day Night	WV (cm)	TA 850 hPa (K)
8001	La Coruña	Spain	43.36	–8.41	67	D	0.27–4.38	266.5–300.8
						N	0.41–3.35	270.7–293.6
8023	Santander	Spain	43.48	–3.8	59	D	0.42–3.59	265.1–297.8
						N	0.77–4.22	265.9–296.4
8160	Zaragoza	Spain	41.66	–1.01	258	D	0.17–3.45	263.1–298.2
						N	n/a	n/a
8190	Barcelona	Spain	41.62	2.2	98	D	0.28–3.87	267.7–299.6
						N	n/a	n/a
8221	Madrid	Spain	40.5	–3.58	633	D	0.17–2.97	266.0–297.6
						N	0.30–3.37	268.7–298.8
8302	Palma de Mallorca	Spain	39.61	2.71	41	D	0.56–3.84	266.9–301.6
						N	n/a	n/a
8430	Murcia	Spain	38.0	–1.16	62	D	0.22–3.38	264.9–301.2
						N	1.15–3.63	276.6–298.0
8495	Gibraltar	UK	36.15	–5.35	4	D	0.33–4.35	263.3–301.4
						N	0.81–4.03	271.3–303.0
8579	Lisboa	Portugal	38.76	–9.13	105	D	0.47–3.34	267.5–297.8
						N	0.84–2.79	274.0–293.6
						D	1.9 ± 0.8	284.6 ± 7.0
						N	1.9 ± 0.8	284.6 ± 7.0
						D and N	1.7 ± 0.7	284.2 ± 6.8

n/a, nonavailable data. Maximum and minimum total column WV and air temperature (TA) at 850 hPa values over the study period are also provided. Mean and 1-sigma standard deviation for WV and TA values extracted from all the stations are provided at the end of the table.

comparison to the amount of valid daytime data (typically around 6–7%), which hampers a direct intercomparison between daytime and nighttime results. However, nighttime data are also included in the results section to provide at least a rough estimation of the accuracy of MOD07 products at nighttime conditions.

3. Results

3.1. Water vapor

Results obtained in the validation of the total column WV are presented in Figure 2. Values extracted from daytime MOD07 show a bias (MOD07 minus radiosonde) of (0.3 ± 0.5) cm, leading to a Root Mean Square Error (RMSE) of 0.55 cm. Nighttime MOD07 values show a negative near to zero bias but higher standard deviation, (–0.1 ± 0.7) cm, with a RMSE of 0.7 cm. Correlation between MOD07 and radiosonde data is higher for daytime acquisitions, with a correlation near to 0.9 versus 0.6 in the nighttime case. Note that almost 94% of the data (5613 values) refers to the daytime case, and only 6% (366 values) to the nighttime case.

Above results were for the WV retrieved by integration from the mixing ratio profiles. MOD07 also includes another total column WV parameter obtained by direct regression from the integrated moisture in the training data. Results obtained for the direct retrieval case (not shown in this paper) were almost similar (0.4 ± 0.5) cm for daytime, with

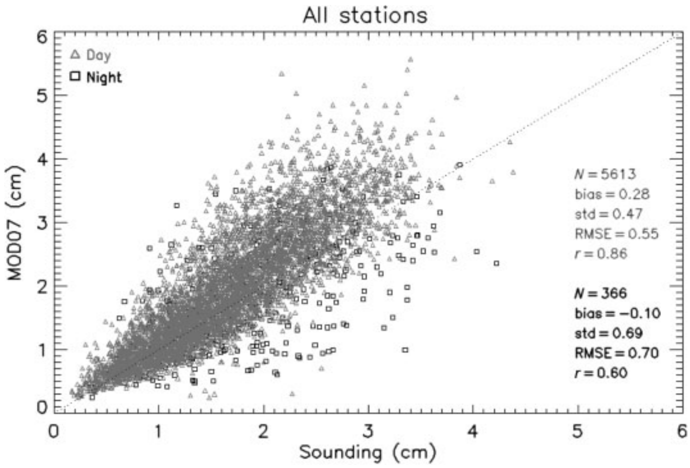

Figure 2. Comparison of total column WV derived from radiosonde data (sounding) with WV extracted from MOD07 product for day and nighttime acquisitions.

correlation near to 0.9, and (0.0 ± 0.7) cm for nighttime, with correlation of 0.6. WV products for 'low' and 'high' contents were also analysed, but improvements were not found when these products were combined.

3.2. Dew point temperature

Figure 3 shows the scatterplots (MOD07 vs. radionsonde) for the dew temperature at some mandatory levels: 1000, 850, 700, 500, 300, 250, 200, and 100 hPa. For nighttime cases, the bias is less than 1 K for pressure levels ranging from 1000 hPa to 850 hPa, with an increasing standard deviation from 4 K to 8 K approximately. Bias values range from 2 K to 3 K for pressure levels between 780 hPa and 500 hPa, with standard deviations around 10 K. Except for 1000 hPa, with a negative bias, the bias is positive until the 500 hPa level (MOD07 overestimation of the dew point temperature). Bias increases to –7 K (±11 K) at 400 hPa, but it significantly decreases for levels between 300 hPa and 150 hPa (with the standard deviation also decreasing). At those pressure levels bias becomes negative. From 100 hPa the bias starts again to increase, and for pressure levels higher than 50 hPa the bias becomes positive and extremely large (higher than 25 K).

Bias values for daytime cases show a similar trend but with higher values than the nighttime cases. Hence, for pressure levels between 1000 hPa and 780 hPa, the daytime bias provides a difference higher than 2 K in comparison with the nighttime, and higher than 4 K for levels between 700 hPa and 400 hPa. Daytime bias is similar to the nighttime bias from 150 hPa. The standard deviation in the daytime is similar but slightly lower than in the nighttime.

3.3. Air temperature

Similar to the dew temperature case, Figure 4 shows the scatterplots (MOD07 vs. radiosonde) for the air temperature at some mandatory levels. For nighttime acquisitions, a bias around 1 K with a standard deviation of around 3 K is found in most cases. Bias is negative from 1000 hPa to 500 hPa, and positive from 300 hPa to 100 hPa. Values of bias

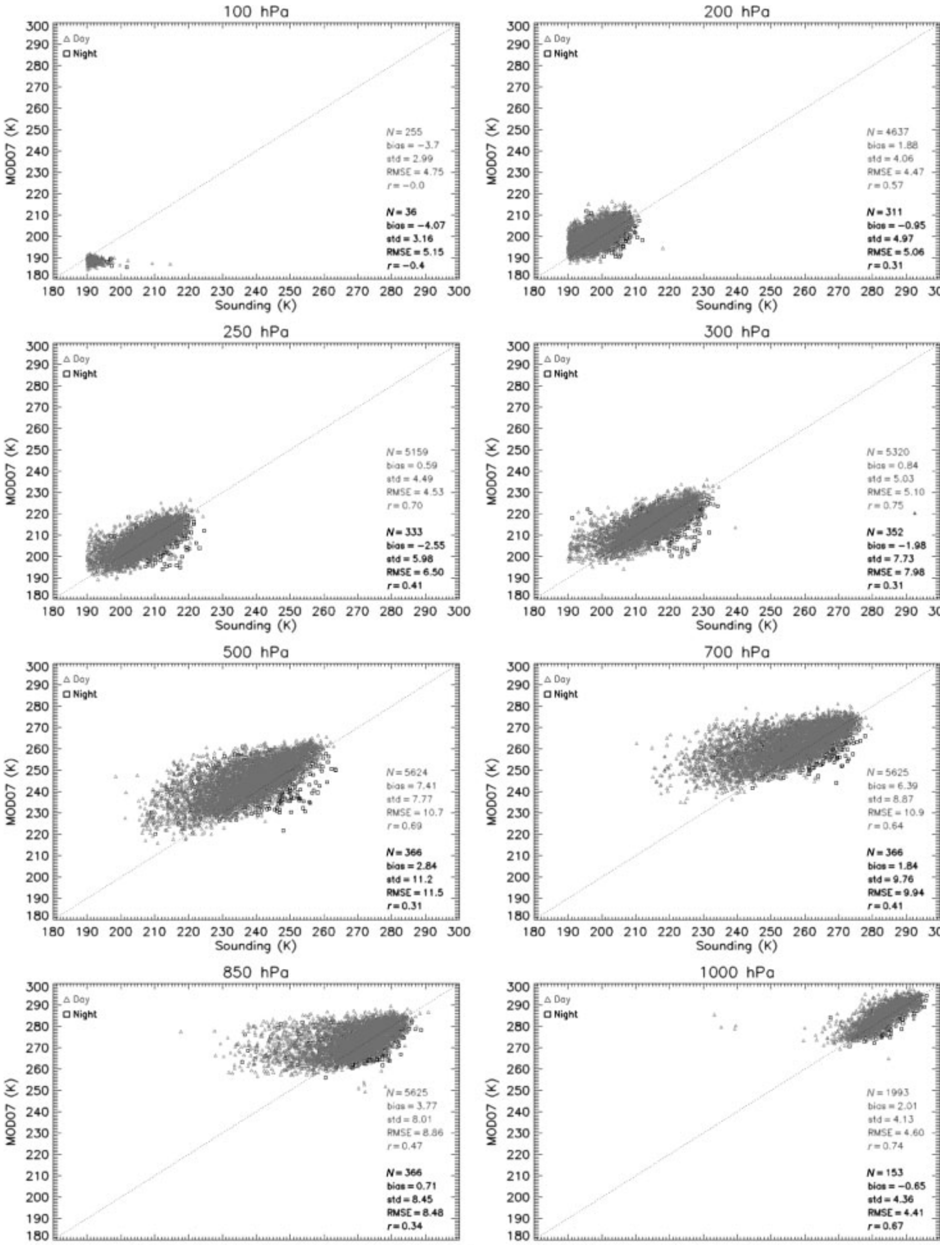

Figure 3. Comparison of dew point temperature measured by the radiosonde (sounding) with dew point temperature extracted from MOD07 product for daytime and nighttime acquisitions at different mandatory pressure levels.

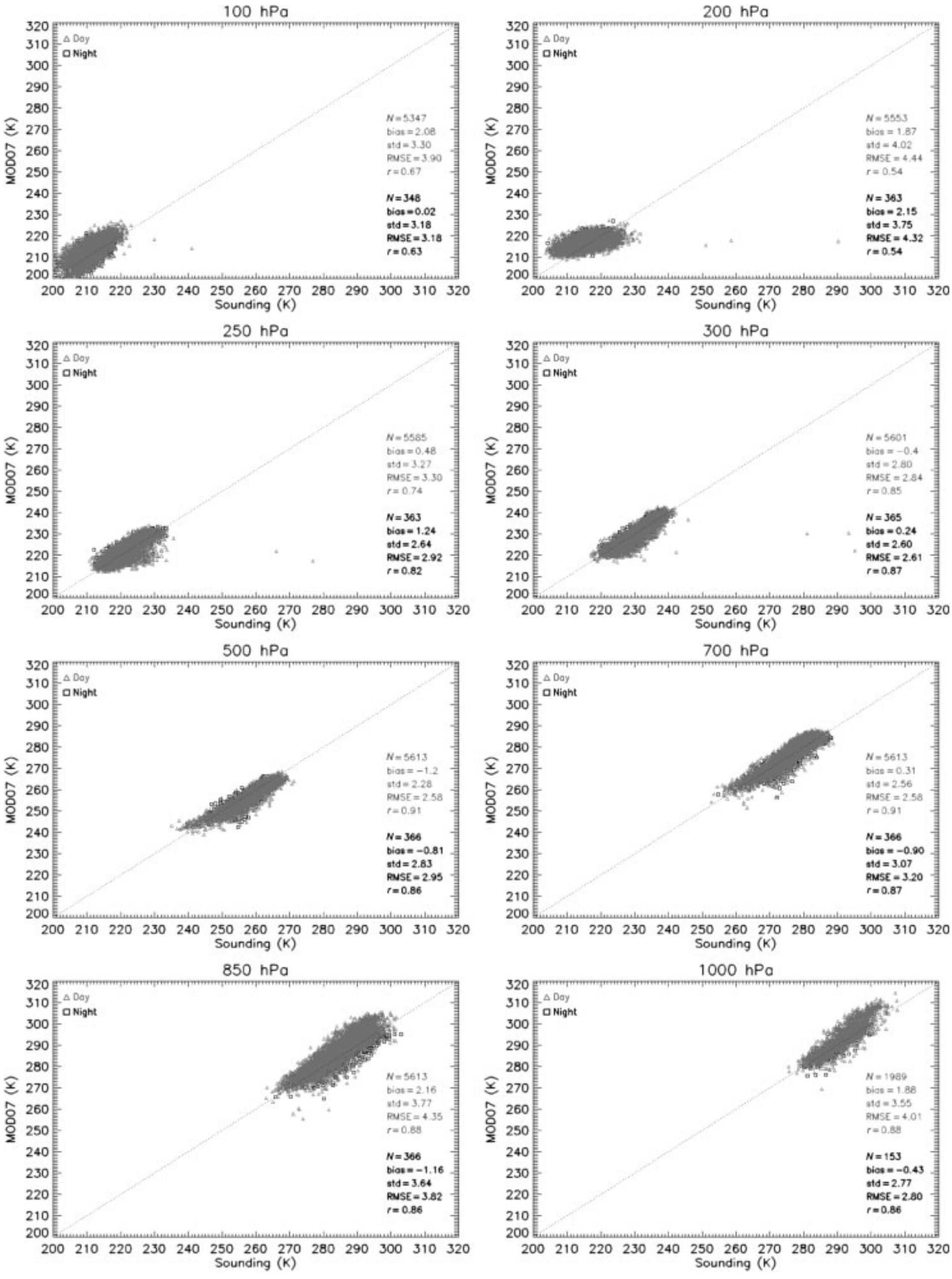

Figure 4. Comparison of air temperature measured by the radiosonde (sounding) with air temperature extracted from MOD07 product for daytime and nighttime acquisitions at different mandatory pressure levels.

were particularly low at 1000 hPa (–0.4 K) and 100 hPa (almost zero), while the highest bias is found at 200 hPa (2.2 K).

Results are roughly similar for daytime cases, although with positive bias at 1000, 850 and 700 hPa levels and with slightly higher standard deviations in some cases. Linear correlation is high in both daytime and nighttime cases ($r > 0.8$, except for 200 and 100 hPa levels, with $r < 0.6$). On average and including both daytime and nighttime acquisitions and including all pressure levels (except for 50, 20, 10, and 5 hPa), the RMSE is around 3.6 K.

Figure 5 shows an example of daytime temporal profiles at 850, 500, and 150 hPa for the radiosonde stations located in Madrid (ID 8221) and Gibraltar (ID 8579). These stations were selected because they include a high percentage of valid data in comparison with other stations. Additionally, Figure 6 shows the monthly relative bias (100 × [MOD07 – radiosonde]/radiosonde) over these two stations. At 850 hPa, the highest values of bias are obtained for the summer months (with July providing the highest

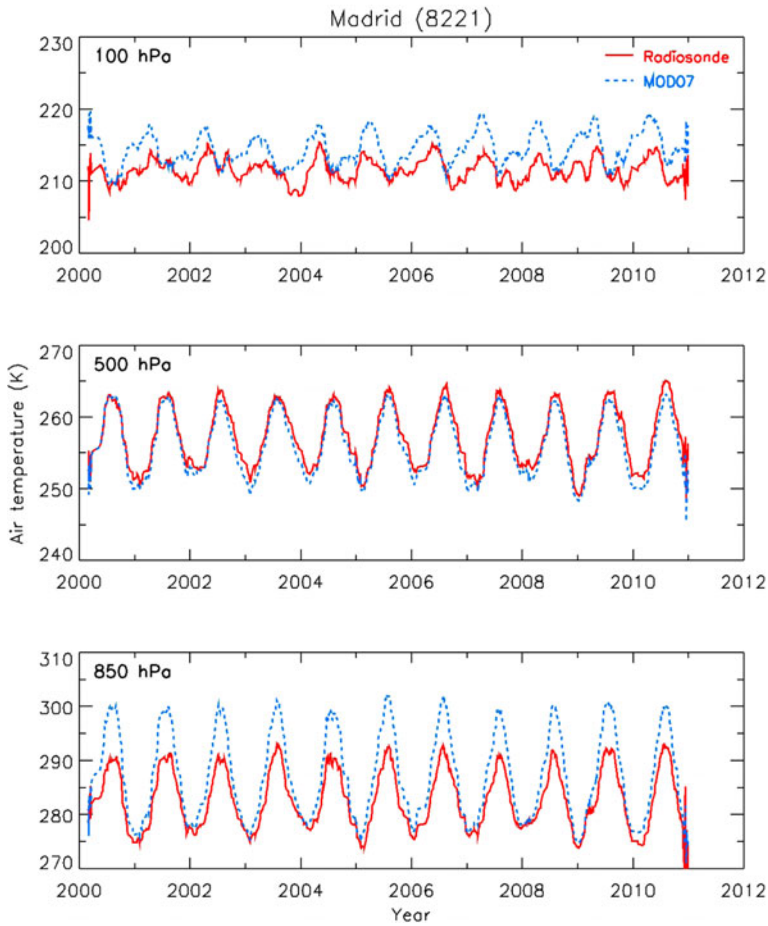

Figure 5. Temporal profiles of air temperature at 850, 500, and 100 hPa obtained from radiosonde measurements (sounding) and MOD07 products over the station ID 8221 (Madrid) and 8579 (Gibraltar). Values have been smoothed for visualization purposes.

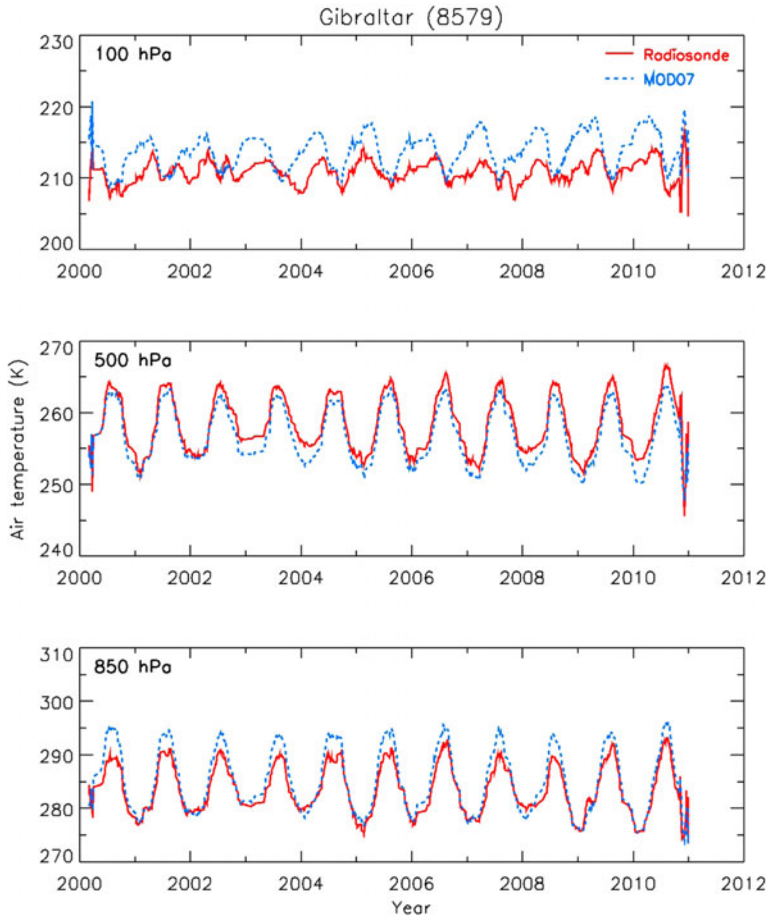

Figure 5. Continued

value), and the lowest values for the winter month (with January and December providing the lowest values). In the case of Madrid station, the relative bias in summer is around 3% (8 K in terms of absolute temperature bias), whereas it is near to zero in winter. Lower bias values were found in Gibraltar station, around 1.5% (4 K) in summer, and also near to zero in winter. However, the bias evolution at 100 hPa is reversed when compared to the bias at 850 hPa. In this case, bias values are lower for summer months than for winter months, with values near to zero in August and values around 2% (between 4 K and 6 K) for January to March and November to December. In the case of 500 hPa, the bias is almost constant and negative, with a magnitude between 0.5% and 1% (1 and 2 K). At 50 hPa, a permanent bias around 7 K was observed in all stations independently of the month, whereas large errors were found in the validation of last pressure levels (results not shown in the paper), so MOD07 retrievals may be less reliable for the higher stratospheric levels.

According to the results presented in Figures 5 and 6, the comparison between MOD07 and radiosonde daytime temporal profiles for the first pressure levels evidences a clear bias during summer (June, July, August), not observed for colder months and

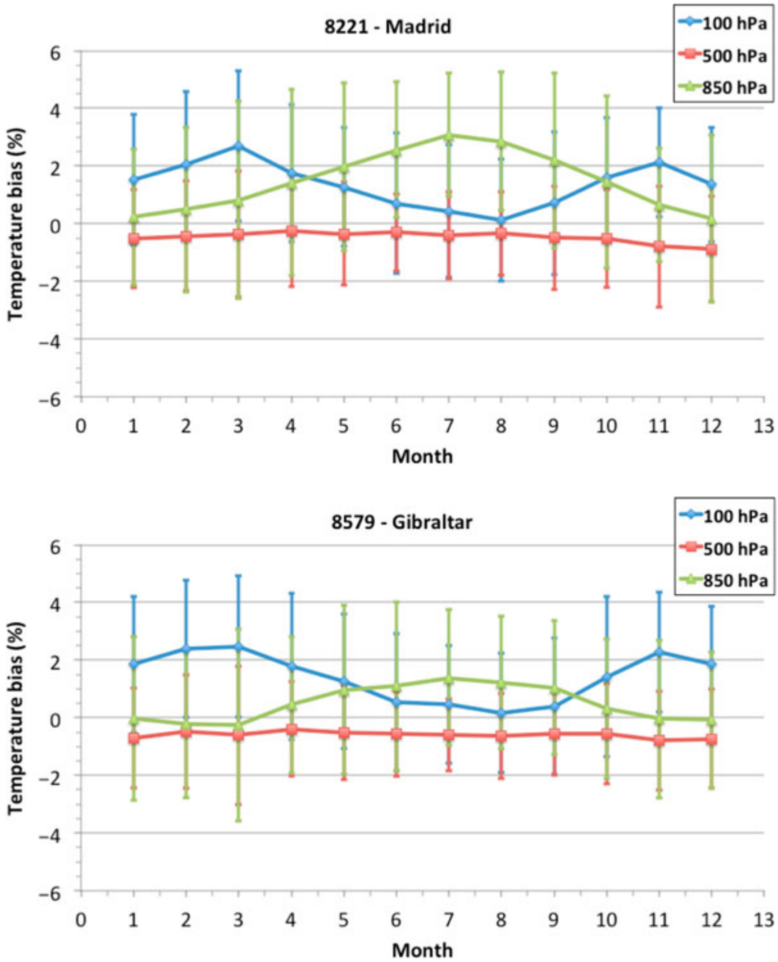

Figure 6. Monthly relative bias (%) in air temperature (mean difference between MOD07 and radiosonde data rationed by the radisonde value, for the period 2000–2010) over stations ID 8221 (Madrid) and ID 8579 (Gibraltar). Results are given for pressure levels at 850, 500, and 100 hPa.

nighttime data. The magnitude of the bias depends on the station and the pressure level. It seems that this bias is higher near the surface (first pressure levels) and for humid and warmer cases.

4. Summary and conclusions

Vertical profiles of air and dew point temperature, as well as total column WV included in the MODIS atmospheric profiles products MOD07 were validated over the Iberian Peninsula at nine different radiosonde stations covering the period from 2000 to 2010. The validation was performed at daily basis and using daytime and nighttime acquisitions. Results were satisfactory for air temperature, with averaged bias (MOD07 minus radiosonde) of 1 K and standard deviation below 3 K, and total column WV, with bias <0.3 cm and standard deviation around 0.5 cm. Results were also satisfactory for the dew point temperature, although in this case higher bias values than in the air temperature case were found: around (2 ± 5) K on average. In both air and dew point temperature cases, MOD07 provided large differences when compared to the radiosonde data for the higher stratospheric levels (from 50 hPa), attributed to the absence of MODIS spectral bands to characterize this atmospheric region, as well as the reduced radiosonde sample sizes in the stratosphere. Although overall results are satisfactory, significant biases where found at some particular levels with a seasonal evolution: levels near the surface (e.g. 850 hPa) show an overestimation of the MOD07 air temperature at summer months, whereas an overestimation of the MOD07 air temperature is observed at winter/spring months for the highest altitude levels (e.g. 100 hPa). In the case of 500 hPa, no seasonal variations were found in the bias.

Results presented in this paper were extracted from the Terra/MODIS v5 derived product, so validation of Aqua/MODIS derived product MYD07 was not performed. It should be also noted that radiosonde data were not corrected by possible technology changes, and no homogenization techniques were applied to the data (Haimberger, Tavolato, and Sperka 2012; Dai et al. 2011). This is not crucial for particular extraction of vertical profiles for atmospheric correction of remote sensing imagery but essential for trend analysis and bias reduction. Validation of the new version of MOD07 products (v6) using homogenized radiosonde data and other climatic records is foreseen by the authors.

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