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Validation of MODIS Terra, AIRS, NCEP/DOE AMIP-II Reanalysis-2, and AERONET Sun photometer derived integrated precipitable water vapor using ground-based GPS receivers over India

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[1] Water vapor is an important and highly variable constituent in time and space; the knowledge of its variability is important in climate studies. In India, the ground observations of water vapor using conventional methods such as radiosonde are limited. In this paper, a comparison of hourly estimates of total column water vapor from Global Positioning System (GPS) with multisensor satellite is presented over three stations. We show quantitatively seasonal and monthly dependency of bias, standard deviation, root mean square error (RMSE), and the correlation coefficient between the water vapor data sets. The GPS and Aerosol Robotic Network (AERONET) water vapor show good agreement (R^2 = 95%, RMSE 3.87 mm, GPS-AERONET bias = −2.63 mm). On the basis of multiple-year data, Moderate Resolution Imaging Spectroradiometer near-infrared (MODIS NIR) clear column product shows higher correlation (R^2 = 89–93%) with GPS compared to infrared (IR) products (R^2 = 82–84%). MODIS is found to be overestimating in NIR clear and IR products in all seasons over India where the magnitude of bias and RMSE show systematic changes from month to month. MODIS is significantly underestimating in NIR cloudy column products during summer and monsoon seasons. MODIS NIR clear column (R^2 = 97%, RMSE 5.44 mm) and IR (R^2 = 81%, RMSE 7.17 mm) water vapor show similar performance on comparison with AERONET data. The MODIS NIR cloudy column product shows no correlation with GPS. The GPS National Centers for Environmental Prediction/Department of Energy Atmospheric Model Intercomparison Project II (GPS-NCEP/DOE AMIP-II) Reanalysis-2 water vapor show R^2 = 87%, 77%, and 60% (and RMSE of 8.39 mm, 6.97 mm, and 9.30 mm) over Kanpur, Hyderabad, and Bangalore, respectively. All the satellite water vapor shows systematic bias with month and season that is found to be sensitive to the sky conditions. The magnitude of bias is invariably larger during monsoon season with relatively more cloudy days and moist atmosphere. The errors in satellite estimation are found to be invariably more during wet compared to dry months. Statistical analysis shows that MODIS NIR clear column and Atmospheric Infrared Sounder (AIRS) daytime water vapor are more reliable compared to other satellite estimates (MODIS IR and AIRS nighttime) except during cloudy days.

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1. Introduction

[2] Atmospheric water vapor plays a major role in the radiative forcing, hydrological cycle, weather and climate [*Rocken et al.*, 1991; *Yuan et al.*, 1993; *Liu et al.*, 2005]. The atmospheric water vapor over the Indian subcontinent and surrounding ocean has a strong seasonal pattern [*Singh et al.*, 2000; *Jade et al.*, 2005; *Prasad et al.*, 2007; *Jade and Vijayan*, 2008]. *Jade and Vijayan* [2008] have shown the GPS PWV (precipitable water vapor) estimates over multiple stations in the Indian subcontinent. The GPS PWV was calculated using meteorological parameters from the local stations and National Centers for Environmental Prediction (NCEP) data. The GPS and Moderate Resolution Imaging Spectroradiometer (MODIS) water vapor show pronounced enhancement of column water vapor with dust storms over the IG plains during 2001–2005 [*Prasad and Singh*, 2007]. Water vapor is found to provide accurate information about the onset of Indian monsoon [*Singh et al.*, 2004]. The GPS derived column water vapor also shows sharp increase in water vapor with the onset of monsoon over India [*Prasad*

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et al., 2007; *Jade and Vijayan*, 2008]. The Indo-Gangetic (IG) plains, home of 600 million people, is one of the agriculturally very productive regions in India. Owing to the growing populations and anthropogenic activities, the Indian monsoon and hydrological cycle, especially of the Indo-Gangetic plains, is found to be affected. In recent years, large deviations in the monsoon rainfall have caused increased droughts and floods over India [*Prasad et al.*, 2006].

[3] Water vapor can be continuously monitored (day and night, hourly average) using GPS. The GPS provides IPWV (integrated precipitable water vapor) or total column water vapor estimates [*Bevis et al.*, 1992, 1994; *Hofman-Wellenhof et al.*, 1992; *Rocken et al.*, 1993, 1997; *Gutman et al.*, 1994; *Businger et al.*, 1996; *Duan et al.*, 1996; *Ware et al.*, 1997, *Bastin et al.*, 2005, *Jade and Vijayan*, 2008]. Accurate estimation of surface pressure and temperature increases the accuracy of GPS water vapor estimates. Over Hyderabad, Kodaikanal and surrounding stations in Asia, the interpolated surface pressure and temperature data obtained from NCEP/NCAR data were found to show good agreement (bias of <1 mbar and <3°C) with local measurements at six GPS sites except at high-altitude sites such as Lhasa.

[4] In recent years, satellite instruments such as MODIS (Moderate Resolution Imaging Spectroradiometer) on Terra, Atmospheric Infrared Sounder (AIRS) on Aqua and other dedicated meteorological satellites provide total column water vapor estimates at high temporal resolution [*King et al.*, 1992, 2003; *Parkinson*, 2003]. These satellites provide daily before-noon, afternoon and nighttime estimates of water vapor. The meteorological satellites of new generation provide data every hour or 3 h. MODIS is a multipurpose satellite with nearly daily global coverage and has been in operation since the year 2000. The MODIS global gridded data (1° × 1° resolution) are being widely used in various atmospheric, biological, monsoon and climate change related studies and are being assimilated into global circulation models. Besides parameters related to aerosols and clouds, MODIS also provides various products related to total column water vapor that are important constituents of global climatological studies [*King et al.*, 1992, 2003]. Common and traditional methods of measurement of water vapor such as radiosonde, radiometer and aircraft have their own limitations [*Rocken et al.*, 1991]. Radiosonde data provide information about the vertical distribution of water vapor but such data are limited and their accuracy is highly in question over the Indian subcontinent.

[5] Satellite sensors such as MODIS on Terra and AIRS on Aqua provide a good spatial and temporal coverage but over the Indian subcontinent, a detailed validation of water vapor data has not been carried out. The GPS water vapor derived using local meteorological data and with NCEP/NCAR shows good agreement over various GPS stations in India [*Jade and Vijayan*, 2008]. The GPS PWV over Bangalore (IISC station) using interpolated and measured meteorological parameters shows bias of 0.3 mm and standard deviation of 0.2 mm. The NCEP PWV and GPS PWV over Bangalore show bias of 2 mm and standard deviation of 4 mm. The GPS water vapor and radiosonde water vapor were found to show bias of 0.7 mm with standard deviation of 4.5 mm over Bangalore in India [*Jade and Vijayan*, 2008]. Recently, validation of MODIS water vapor using GPS data has been carried out over Germany [*Li et al.*, 2003] and Tibetan Plateau [*Liu et al.*, 2006]. Several studies over different parts of the world on GPS water vapor versus ground-based water vapor (radiosonde, radiometer) and research aircraft measurements have shown a very high correlation (R^2 = 0.99) [*Niell et al.*, 2001; *Bock et al.*, 2005; *Liu et al.*, 2005; *Mattioli et al.*, 2005; *van Baelen et al.*, 2005]. The radiosonde stations over Europe show an overall bias of 4.5% compared to GPS. The largest differences were observed in mountainous and coastal areas [*Bock et al.*, 2005]. The GPS and microwave radiometer derived PWV, over a 14-day period, generally agreed within 1 mm [*Niell et al.*, 2001]. The GPS and radiosonde PWV observations over three stations in Tibetan Plateau (Naqu, Gaize, and Deqin) show an average difference of 1.75 mm. The average difference between GPS and operational numerical weather prediction (NWP) PWV was found to be 7.75 mm [*Liu et al.*, 2005]. The differences between GPS and three microwave radiometers (at 23.8 and 31.4 GHz) derived PWV at a ARM (Atmospheric Radiation Measurement Program's) site in north-central Oklahoma are found to be within 1 mm during year 2003 [*Mattioli et al.*, 2005]. Over a 3-month campaign at Toulouse, France (year 2002), the GPS estimates were generally found be higher than radiosonde by up to 2 mm during the day and by less than 0.5 mm during the night. The diurnal difference between the two estimates was attributed to the daytime dry bias of radiosonde. In comparison, the GPS and microwave PWV show less difference (0–1 mm) [*van Baelen et al.*, 2005]. *Yang et al.* [1999] compared GPS water vapor estimates with High-Resolution Limited Area Model (HIRLAM) data assimilation (reanalysis) and observed usefulness of GPS for meteorological applications. *Glowacki et al.* [2006] have compared GPS and radiosonde over eight stations over Australia and found the standard error to be 8%. Relatively, the GPS and 6-hour forecasts of the Australian Bureau of Meteorology's show 18.0% error. *Glowacki et al.* [2006] have shown potential of GPS estimates in reducing the errors in water vapor estimates from other sources. The temperature and water vapor retrievals from the AIRS were found to be in good agreement with the global radiosonde measurements [*Divakarla et al.*, 2006]. Using global radiosonde water vapor measurements as a reference, the RMS difference with AIRS measurements show better than 15% in 2-km layers in the troposphere (for clear-only cases over sea and land-sea-coast combined). *Raja et al.* [2008] have discussed the use of GPS water vapor data as a validation tool for AIRS data. On comparison with GPS, *Raja et al.* [2008] have found systematic seasonal bias in the estimation of water vapor by AIRS over the United States and

Figure 1. (a) Location of GPS stations Kanpur, Hyderabad, and Bangalore over India and other GPS stations which are considered in the present GPS data processing. (b) The correlation between water vapor from GPS and AERONET (Sun photometer), (c) the bias (GPS – AERONET), (d) the standard deviation of water vapor estimation by GPS, (e) the standard deviation of water vapor estimation by AERONET, and (f) monthly variability of correlation statistics (R^2, bias, RMSE, and standard deviation) during various seasons over Kanpur station (2004–2007) in India.

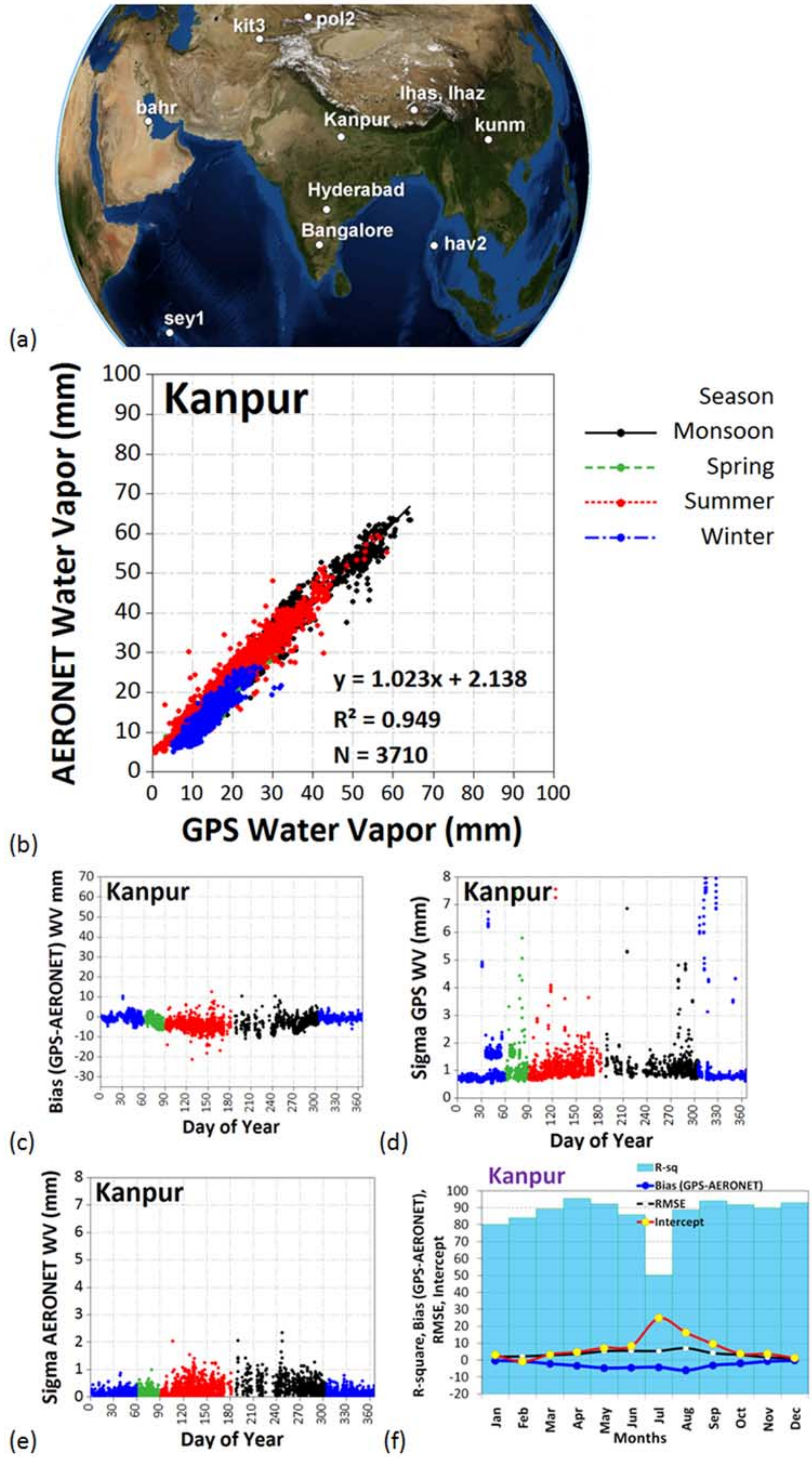
kit3
pol2
lhas, lhaz
bahr
Kanpur
kunm
Hyderabad
Bangalore
hav2
sey1
(a)
Kanpur
Season
Monsoon
Spring
Summer
Winter
AERONET Water Vapor (mm)
GPS Water Vapor (mm)
y = 1.023x + 2.138
R² = 0.949
N = 3710
(b)
Bias (GPS-AERONET) WV mm
Day of Year
(c)
Sigma GPS WV (mm)
(d)
Sigma AERONET WV (mm)
(e)
R-sq
Bias (GPS-AERONET)
RMSE
Intercept
R-square, Bias (GPS-AERONET), RMSE, Intercept
Months
(f)

Figure 1

Table 1. Details of the Sources of Water Vapor Estimates Used in This Study

Serial Number	Stations	Sensor	Detail	Collection Time	Spatial Resolution	Temporal Resolution	Data Range: Years
1	Kanpur	GPS	dual frequency	all day		hourly	2004–2007
2	Hyderabad	GPS	dual frequency	all day		hourly	2002–2007
3	Bangalore	GPS	dual frequency	all day		hourly	1996–2007
4	Kanpur	AERONET	sun-photometer	day		few minutes (∼15min.)	2001–2007
5	Kanpur	MODIS Terra	near- infrared clear column	day	1°	daily	2000–2007
6	Hyderabad	MODIS Terra	near- infrared clear column	day	1°	daily	2000–2007
7	Bangalore	MODIS Terra	near- infrared clear column	day	1°	daily	2000–2007
8	Kanpur	MODIS Terra	infrared	day	1°	daily	2000–2007
9	Hyderabad	MODIS Terra	infrared	day	1°	daily	2000–2007
10	Bangalore	MODIS Terra	infrared	day	1°	daily	2000–2007
11	Kanpur	MODIS Terra	near-infrared cloudy column	day	1°	daily	2000–2007
12	Hyderabad	MODIS Terra	near-infrared cloudy column	day	1°	daily	2000–2007
13	Bangalore	MODIS Terra	near-infrared cloudy column	day	1°	daily	2000–2007
14	Kanpur	NCEP-DOE	Reanalysis-2	0000, 0600, 1200, 1800 UT	2.5°	6 hourly	1996–2007
15	Hyderabad	NCEP-DOE	Reanalysis-2	0000, 0600, 1200, 1800 UT	2.5°	6 hourly	1996–2007
16	Bangalore	NCEP-DOE	Reanalysis-2	0000, 0600, 1200, 1800 UT	2.5°	6 hourly	1996–2007
17	Kanpur	AIRS	ascending mode	day	1°	daily	2002–2007
18	Hyderabad	AIRS	ascending mode	day	1°	daily	2002–2007
19	Bangalore	AIRS	ascending mode	day	1°	daily	2002–2007
20	Kanpur	AIRS	descending mode	night	1°	daily	2002–2007
21	Hyderabad	AIRS	descending mode	night	1°	daily	2002–2007
22	Bangalore	AIRS	descending mode	night	1°	daily	2002–2007

discussed the importance of spatial and temporal collocation on the bias, root mean square error (RMSE) and standard deviation of differences. The surface pressure differences between GPS and AIRS retrieval algorithm also affects accuracy of AIRS water vapor estimates. A decrease in spatial and temporal collocation causes increase in bias and RMSE.

[6] In recent years, GPS estimates of column water vapor have emerged as a good substitute for traditional systems (such as radiosonde). National Oceanic and Atmospheric Administration (NOAA) provides realtime estimates of GPS water vapor over a network of more than 375 GPS locations over the United States (http://gpsmet.noaa.gov). Currently, relative accuracy of GPS derived water vapor is well established compared to other ground-based instruments such as radiosonde and radiometer [*Bock et al.*, 2005; *Liu et al.*, 2005; *Mattioli et al.*, 2005; *van Baelen et al.*, 2005]. However, accuracy of satellite derived water vapor such as that of MODIS, AIRS and other sources such as National Centers for Environmental Prediction/Department of Energy Atmospheric Model Intercomparison Project II (NCEP/DOE AMIP-II) Reanalysis-2, that is also used for cloud, monsoon and radiative forcing studies, are not well known, especially over India. We have carried out detailed analysis of GPS, Aerosol Robotic Network (AERONET), NCEP/DOE AMIP-II Reanalysis-2 and satellite (MODIS, AIRS) water vapor over Kanpur (IITK: 26.28°N, 80.24°E) lying in the central part of IG plains and two stations in the southern parts of India (Hyderabad and Bangalore) (HYDE: 17.20°N, 78.30°E and IISC: 12.58°N, 77.38°E) located over the Indian peninsular shield region (Figure 1a). The aim is to study variability and accuracy of satellite (MODIS, AIRS), NCEP/DOE AMIP-II derived water vapor with GPS and AERONET derived water vapor. Accurate estimation of satellite water vapor data available as a $1^\circ \times 1^\circ$ grid product is very important as it covers the whole globe and is an integral part of the global circulation model and other areas of atmospheric research [*Kuo et al.*, 1993; *Yuan et al.*, 1993; *Liu et al.*, 2005]. We have carried out relatively long-term (multiyear) analysis of bias, standard deviation, root mean square error (RMSE) and the correlation coefficient between two independent data sets. We have compared GPS and AERONET, independent in terms of measurement principle, sampling process, and methodology. We have further carried out validation and detailed monthly and seasonal analysis of multiple MODIS Terra (before noon) water vapor products in near-infrared (NIR), infrared regions, AIRS water vapor product in afternoon (ascending mode) and nighttime (descending mode) and NCEP/DOE AMIP-II Reanalysis-2 (6-hourly individual observations). We have compared the seasonal and monthly dependency of bias with previous studies over other regions. Relative accuracy of satellite products (MODIS, AIRS) have been discussed with major trends in the observed bias with month (dry and wet) and season.

2. Water Vapor Data

[7] The climate over India is characterized by four distinct seasons. Generally, the hottest months from April

to June are regarded as the summer season while the coldest months from November to February are regarded as the winter season. December and January are the coldest months, peak of winter season, over India. The rainy or monsoon season normally starts in July and extends up to October. Most of the rainfall over India is received during these 4 months. There is a short spring season during March which signifies a transition period of change in weather from cold conditions to hot summer months. We have classified our water vapor data (Table 1) to these four seasons to study the seasonal dependency of bias.

2.1. GPS

[8] We have used Trimble survey grade dual frequency receiver (Trimble 5700 with Zephyr geodetic antenna) data for Kanpur station. The Trimble GPS uses satellite radio signals at 1.2 and 1.5 GHz. The GPS data in rinex format for permanent IGS (International GNSS Service) stations (Hyderabad and Bangalore) have been obtained from Scripps Orbit and Permanent Array Center (SOPAC, http://sopac.ucsd.edu/). Satellite radio signals traveling from space to the ground GPS receiver is delayed by the atmosphere (troposphere) and ionosphere. After ionospheric correction, using a linear combination of L1 and L2 frequencies (1.2 and 1.5 GHz), the delay in signal measured by the ground receiver is induced by the troposphere. The tropospheric delay consists of two parts: dry delay and wet delay. Dry delay, due to atmospheric gases, can be accurately modeled by using surface pressure data (from either NCEP or local barometer), and wet delay is obtained from the difference between total and dry delay. The zenith wet delay due to water vapor in the atmosphere is calculated in an absolute sense that is precipitable water vapor. Therefore, accuracy of GPS water vapor measurements partly depends on the accuracy of surface pressure measurements [*Bevis et al.*, 1992, 1994; *Duan et al.*, 1996; *Ware et al.*, 1997]. In the absence of local meteorological data or met-package, we have used the inbuilt script to compute zenith wet delay and precipitable water from MODEL z-files (http://chandler.mit.edu/~simon/gtgk/GAMIT_Ref_10.3.pdf) containing record of meteorological values. The processing of the GPS signal has been carried out using GAMIT/GLOBK software (http://www-gpsg.mit.edu/~simon/gtgk/) which is a standard processing tool for the retrieval of water vapor column (GAMIT Reference Manual, 2006, available at http://chandler.mit.edu/~simon/gtgk/GAMIT_Ref_10.3.pdf). We have set up a network of GPS stations including iitk (Kanpur, India), hyde (Hyderabad, India), iisc (Bangalore, India), lhas (Lahasa, Tibet, China), Lhaz (Lahasa, Tibet, China), kunm (Kunming, Yunnan, China), pol2 (Poligan, Bishkek, Kyrghyzstan), sey1 (Seychelles, La Misere, Mahe Island, Republic of Seychelles), kit3 (Kitab, Uzbekistan), bahr (Bahrain, Manama, Bahrain), hav2 (Havelock, Andaman Islands, India) (http://sopac.ucsd.edu) for processing. The lhas station is operational as of 1995; the data obtained from this station is used in the present study since 1996. In the absence of data from lhas (29.66°N, 91.1°E), data from another close-by IGS station lhaz (29.66°N, 91.1°E) have been used for processing data of recent years. The GPS is capable of providing continuous (day and night), all-weather, calibration and drift-free (instrumental) measurement of total column water vapor. Integrated total column water vapor has been retrieved from GPS data as hourly average with errors normally less than 1–2 mm. Hourly averages of GPS water vapor have been compared with corresponding hour data from satellites (MODIS, AIRS), AERONET Sun photometer and NCEP/DOE AMIP-II Reanalysis-2 water vapor.

2.2. AERONET

[9] The AERONET Sun photometer network is primarily used for aerosol studies [*Holben et al.*, 1998]. The AERONET Sun-sky radiometers measure direct Sun and sky radiance in multiple channels for the retrieval of aerosol parameters. The column water vapor product is obtained using the 936-nm channel and is used for correction in the aerosol retrieval algorithm. It is emphasized that high-accuracy AOD (0.01–0.02 [*Eck et al.*, 1999]) from AERONET result in relatively small error in estimated AOD at 936 nm based on Angstrom extrapolation from 675- and 870-nm data. This results in minimal aerosol influence on the accuracy of the PWV retrieval from AERONET. We have used the AERONET derived water vapor product (Version 2 Direct Sun Algorithm, level-2 quality assured) for the period 2000–2007. The data set (v2, l2) is cloud-cleared [*Smirnov et al.*, 2000], inspected, calibrated, and recommended for further studies (http://aeronet.gsfc.nasa.gov). We have obtained all points available in a day for the above period and taken up first measurement of water vapor as representative of that hour and compared with the corresponding hour value from GPS, MODIS and AIRS. The AERONET derived column water vapor represents only daytime and sky conditions where the Sun is unobscured by clouds. We have carried out comparison with only infrared region, and clear column water vapor in NIR region from MODIS (before noon) and AIRS (daytime, afternoon). The first estimate of AERONET water vapor for each hour has been paired with corresponding GPS estimate for comparison. The GPS-AERONET pairs cover all daytime hourly data during which AERONET values are available for the period 2004–2007.

2.3. MODIS Terra

[10] MODIS is a major instrument onboard the EOS (Earth Observing System) polar orbiting Terra satellite on a global scale every 1 to 2 days. MODIS has higher spatial resolution (250 m at nadir), wide swath (2330 km), and large spectral range (36 channels between 0.412 to 14.2 μm). The channels between 0.4 and 2.1 μm are useful for retrieval of aerosol properties, while five channels in near-infrared (0.865, 0.905, 0.936, 0.940, and 1.24 μm) are useful for remote sensing of water vapor [*King et al.*, 1992, 2003; *Gao and Kaufman*, 2003; *Remer et al.* 2005]. We have used level-3 MODIS Terra (MOD08_D3, http://modis-atmos.gsfc.nasa.gov/) daily global gridded product with standard deviation. A validation of level-3 version-5 gridded product is particularly useful as it is going into global models for weather and climate change studies. We have used three water vapor products from MODIS Terra: near-infrared (NIR) clear column, NIR cloudy column and infrared (IR) water vapor having spatial resolution of 1°, and these are particularly useful to study interaction

between aerosols, energy budget and hydrological cycle [*Gao and Kaufman*, 2003] (also B. C. Gao and Y. J. Kaufman, The MODIS Near-IR water vapor algorithm, Products: MOD05, MOD08, 1998, available at http://modis-atmos.gsfc.nasa.gov/_docs/atbd_mod03.pdf) (hereinafter Gao and Kaufman, online document, 1998). The sensitivity analysis of channel ratio techniques shows that a 0.01 error in derived transmittance gives roughly 2.5% error in the retrieved column water vapor. However, errors can be 10% or slightly greater if the aerosol effects are not corrected under hazy conditions (visibilities <10 km) or when the surface reflectance near 1 mm is small (less than about 0.1) (Gao and Kaufman, online document, 1998). MODIS instrument onboard Terra satellite usually passes over the study region between 1030–1130 local time (LT) and gives estimates of column water vapor as three major products: NIR clear column, NIR cloudy column and IR. The corresponding hourly estimates of GPS water vapor during daytime, at 5-h GMT (average of 1030–1130 LT) have been used to assess accuracy of these three products.

2.4. NCEP/DOE AMIP-II Reanalysis-2

[11] We have used precipitable water vapor from NCEP/DOE AMIP-II Reanalysis-2 [*Kanamitsu et al.*, 2002] data available 4 times daily (at an interval of 6 h) for the entire globe at a spatial resolution (grid) of 2.5°. The long name of the data set is "6-Hourly Precipitable Water for Entire Atmosphere" (units: kg/m^2). The NCEP/DOE AMIP-II data have been extracted over three stations, Kanpur, Hyderabad and Bangalore, since 1996 for comparison with GPS data. The 6-hourly individual data from NCEP/DOE AMIP-II were time collocated with corresponding hourly estimate from GPS. As the size of the grid of NCEP/DOE AMIP-II, data are relatively large (2.5°); there is a large distance between the location of the GPS station and the center of the NCEP/DOE AMIP-II pixel for Hyderabad and Bangalore. The Hyderabad and Bangalore are located close to the corner of $2.5° \times 2.5°$ pixel. This spatial mismatch is likely to affect correlation and bias study over these two stations.

2.5. Atmospheric Infrared Sounder (AIRS)

[12] The AIRS is one of the three sensors onboard Aqua that is capable of providing estimates of water vapor in the atmosphere [*Parkinson*, 2003]. We have used AIRS/Aqua level-3 daily standard physical retrieval product (Without HSB) V005 (AIRX3STD) available at Goddard Earth Sciences Data and Information Services Center (GES DISC) (http://mirador.gsfc.nasa.gov/collections/AIRX3STD__5.shtml). The AIRX3STD product used here is without HSB (Humidity Sounder for Brazil). The spatial resolution of the water vapor product used is $1° \times 1°$. The total column water vapor data from ascending (daytime) (TotH2OVap_A) and descending (nighttime) mode (TotH2OVap_D) have been used (units: kg/m^2). The AIRS in ascending mode crosses equator at around 0130 LT and descending mode at around 1330 LT. Details about AIRS instrumentation, retrieval algorithm, effect of cloud and overcast conditions is given by *Aumann et al.* [2003], *Divakarla et al.* [2006], *Raja et al.* [2008], and *Susskind et al.* [2003]. AIRS level-3 version-5 total column water vapor is available at 1° spatial resolution since 2002. We have used daytime and nighttime AIRS estimates and paired them with corresponding hour estimates from GPS to assess accuracy of AIRS water vapor retrieval. Surface pressure, temperature, and clouds or overcast conditions are known to cause major uncertainties in the retrieval of water vapor from AIRS [*Raja et al.*, 2008].

2.6. Variability of GPS Water Vapor Over India

[13] The GPS water vapor over Kanpur shows large fluctuations during months and seasons. Daily average GPS water vapor over Kanpur is found to be lowest during April (<10 mm in the beginning of summer or premonsoon season) and found to increase, up to 40 mm, until the onset of monsoon season (third week of June, India Meteorological Department (IMD), http://www.imd.ernet.in/). The monthly mean GPS water vapor over Kanpur is found to be 16.73 ± 7.22 mm, 25.73 ± 8.23 mm, and 39.10 ± 12.53 mm during April, May and June (summer season), respectively. The Hyderabad also show gradual increase in GPS water vapor during April (27.89 ± 7.06 mm), May (30.53 ± 8.12 mm), and June (44.48 ± 6.53 mm). Similarly, the monthly GPS water vapor over Bangalore shows an increasing trend (25.76 ± 6.51 mm, 32.56 ± 5.46 mm, and 37.22 ± 4.44 mm during April, May and June, respectively). A gradual increase in total column water vapor is found to be associated with the increase of ground temperature during April–June. A number of dust storms originating from the Arabia peninsula and western arid and desert regions are found to affect the air quality of the IG plains during premonsoon period (April–June) [*Dey et al.*, 2004; *Singh et al.*, 2004; *Prasad and Singh*, 2007]. An enhancement of water vapor is found to be associated during dust storms; these dust storms generally traverse through the Arabian ocean, bringing moisture along with dust [*Prasad and Singh*, 2007] over the IG plains. A large increase in daily water vapor, up to 70 mm, is observed during the monsoon onset (June–July) followed by break (low water vapor, <50 mm) phase [*Prasad et al.*, 2007]. During monsoon months, the monthly GPS water vapor over Kanpur is found to be about 57.77 ± 6.02 mm (July), 54.03 ± 7.71 mm (August), 45.52 ± 10.32 mm (September), and 22.74 ± 8.99 mm (October). The wet season (monsoon, July–October) is mostly cloudy and receives the maximum amount of rainfall in a year. The GPS water vapor shows pronounced decrease in water vapor (22.74 ± 8.99 mm over Kanpur) beginning in October owing to the withdrawal of the southwest monsoon. The daily average water vapor is generally found to be less than 20 mm during the winter season (November–January). The monthly mean GPS water vapor over Kanpur is found to be 14.06 ± 4.35 mm, 12.17 ± 5.34 mm, 17.34 ± 4.00 mm, and 15.38 ± 4.53 mm during November, December, January and February, respectively. The monthly mean GPS water vapor over Hyderabad is found to be 21.49 ± 9.01 mm, 16.70 ± 5.50 mm, 18.02 ± 6.00 mm, and 18.38 ± 4.73 mm during November, December, January and February, respectively. The monthly mean GPS water vapor over Bangalore is 27.97 ± 9.60 mm, 19.11 ± 9.02 mm, 16.62 ± 6.55 mm, 16.07 ± 6.66 mm during November, December, January and February, respectively. The monthly GPS water vapor during spring season (March) is 16.25 ± 6.33 mm, 21.70 ± 7.06 mm, and 18.94 ± 6.78 mm over Kanpur, Hyderabad, and Bangalore, respectively. Hyderabad and Bangalore are located in the

Table 2. Seasonal Statistics and Correlations Between the Water Vapor Simultaneously Measured by GPS and AERONET Sun Photometer at the Kanpur Station, 2004–2007[a]

Season	Number of Pairs	Bias (GPS − AERONET) (mm)	Standard Deviation (mm)	RMSE (mm)	Linear Regression (GPS and AERONET)		
					R^2	Slope	Intercept
Annual	3710	−2.63	2.84	3.87	0.95	1.02	2.14
Winter	1027	−0.55	1.82	1.90	0.85	0.94	1.32
Summer	1428	−4.06	2.54	4.79	0.94	0.96	5.03
Monsoon	839	−3.00	3.07	4.29	0.95	0.99	3.37
Spring	416	−2.11	2.07	2.96	0.89	0.93	3.36

[a]Water vapor is integrated precipitable water vapor. Time was collocated by same hour, hourly daytime data.

southern peninsular India where the variability of water vapor is found to be less. Hyderabad and Bangalore shows less increase in water vapor compared to Kanpur during the monsoon season (43.93 mm over Hyderabad and 37.36 mm over Bangalore). The GPS data show higher column water vapor over Hyderabad and Bangalore during the winter season compared to Kanpur due to their proximity to the ocean. Kanpur is an inland station that is located in the northern plains of India and adjacent to the towering Himalayan mountain range in the north, and occasionally influenced by dry air from the deserts to the west and the Tibet plateau to the north.

3. Validation

3.1. GPS and AERONET Water Vapor

[14] The GPS and AERONET derived water vapor over Kanpur show good correlation for period 2004–2007 with R^2 ~0.95 for N = 3710 pairs, with RMSE 3.87 mm (Figure 1b and Table 2). The AERONET data show bias (GPS-AERONET) of −2.63 mm (overestimation) over 4 years. Seasonal decomposition of R^2 shows good correlation of 0.94 and 0.95 during summer and monsoon seasons, respectively. The AERONET Sun photometer gives good water vapor estimates in all seasons including the monsoon season as it can operate and measure only during sky conditions where the direct view of the Sun is unobscured by clouds. This explains relatively high correlation between GPS and AERONET during the monsoon season. The AERONET data show low seasonal mean bias (overestimation) of −0.55 mm during winter season compared to −4.06, −3.00, −2.11 mm during summer, monsoon and spring seasons, respectively (Table 2). The GPS-AERONET bias as percent of mean seasonal AERONET values is −3.98%, −15.67%, −8.31%, −11.13% and −11.13% for winter, summer, monsoon, spring and all season respectively. The daily bias, grouped as monthly and seasonal (Figure 1c), shows relatively higher bias (overestimation by AERONET) during summer and monsoon seasons (mostly 0 to −10 mm) compared to winter season (0 to ±5 mm). The standard deviation of daily GPS water vapor is also found to be relatively lower (<1 mm) during winter season, afterward found to increase gradually during summer (mostly 1–2 mm), and monsoon seasons (Figure 1d). During the winter months (December and January, 2004–2007), the GPS water vapor standard deviation is found to more than 3 mm, for only 6 days (over Kanpur). The hourly data for whole day show large standard deviation >3, which is also found for another station (Hyderabad) on the same days. The propagation of the error in water vapor retrieval to other stations on the same days suggests that the retrieval procedure suffers from a common problem such as ionosphere correction or is associated with the orbit files. Similarly, standard deviation in the estimation of water vapor by AERONET is found to be lower (0–0.5 mm) during winter season and increases (mostly 0–1 mm) during summer and monsoon seasons (Figure 1e). The errors in the estimation are found to be relatively higher during summer and monsoon seasons compared to the winter. The standard deviation of AERONET water vapor is found to be lower than GPS because the variations in ionosphere, and local pressure and temperature induce large proportion of total error in water vapor retrieval from GPS. The total error can be minimized in the estimation of water vapor if the local meteorological package data could be available with the GPS locations, which is absent for stations use in this study, and better modeling of ionosphere would help in reducing the standard deviation from GPS estimation, and it would be more comparable to AERONET standard deviation. The AERONET utilizes a different principle for water vapor estimation. The largest uncertainty in AERONET water vapor is induced by thin clouds and is independent of precise measurement of local temperature and pressure measurements and ionosphere variations. The AERONET standard deviation also shows gradual increase during the monsoon months. Table 2 shows seasonal and Figure 1f shows monthly breakdown of behavior of GPS and AERONET data. Figure 1f shows lowest correlation between GPS and AERONET during July month (R^2 ~0.5), at the time of monsoon onset when higher cloud fractions are found. In general, the ground-based independent instruments (GPS and AERONET Sun photometer) provide reliable estimates of column water vapor except during monsoon month (July). July is characterized by the onset of monsoon over India with substantial lightning activities, and an increase in the local variations of temperature and pressure, which induces large error in the GPS estimates (without local meteorological package data). July also represents a transition phase in weather from dry and hot summer months to wet and relatively cold rainy season. Besides, the increase in cloud fraction during July causes degradation of the clear Sun-sky view by AERONET, which induces error in the AERONET measurements. The increase in measurement errors in both GPS and AERONET causes multiplication of error leading to a substantial decrease in the correlation

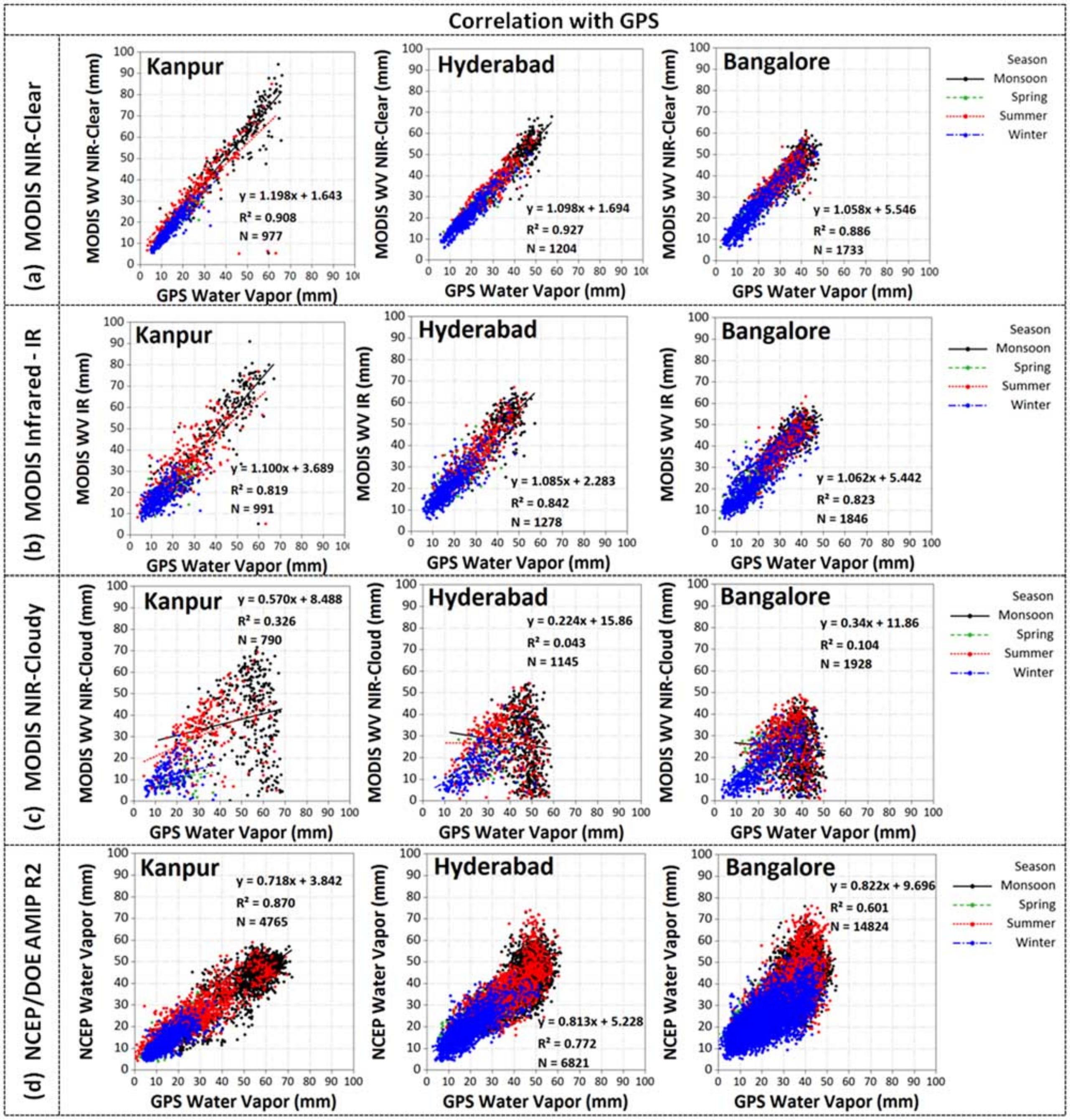

Figure 2. Correlation between water vapor from (a) daily MODIS NIR clear column and GPS, (b) daily MODIS infrared (IR) column and GPS, (c) daily MODIS NIR cloudy column and GPS, and (d) 6-hourly NCEP/DOE AMIP Reanalysis-2 and GPS over Kanpur (2004–2007), Hyderabad (2002–2007), and Bangalore (1996–2007) stations in India.

during July (Figure 1f). In sections 3.2–3.6, we have used column water vapor data from GPS and AERONET data to validate and estimate bias in the satellite derived column water vapor.

3.2. GPS and MODIS Terra Water Vapor

[15] The seasonal validation of MODIS Terra with GPS data is shown for Kanpur, Hyderabad, and Bangalore stations. Earlier studies show higher correlation coefficients (>0.98) between GPS and MODIS (collection 3) over Germany [*Li et al.*, 2003]. *Li et al.* [2003] have shown that MODIS water vapor is overestimated compared to GPS over Germany with scale factors from 1.07 to 1.14. In contrast, *Liu et al.* [2006] have found underestimation of MODIS water vapor compared to GPS over Tibetan Plateau (Stations: Gaize and Naqu). The MODIS and GPS PWV

Table 3. Seasonal Statistics and Correlations Between the Water Vapor Simultaneously Measured by GPS and MODIS NIR Clear Column at the Kanpur, Hyderabad, and Bangalore Stations[a]

Station (Period)	Season	Number of Pairs	Bias (GPS − MODIS) (mm)	Standard Deviation (mm)	RMSE (mm)	Linear Regression (GPS and MODIS NIR Clear) R^2	Slope	Intercept
Kanpur (2004–2007)	Annual	977	−6.58	6.67	9.37	0.91	1.20	1.64
	Winter	355	−3.06	2.50	3.95	0.85	1.07	2.04
	Summer	242	−7.84	7.72	11.00	0.70	0.97	8.50
	Monsoon	296	−10.51	7.43	12.87	0.89	1.20	2.66
	Spring	84	−4.02	2.71	4.85	0.85	0.98	4.34
Hyderabad (2002−2007)	Annual	1204	−4.34	3.95	5.87	0.93	1.10	1.69
	Winter	517	−2.78	2.72	3.89	0.89	1.01	2.58
	Summer	250	−5.61	3.95	6.86	0.82	0.98	6.15
	Monsoon	305	−6.10	4.93	7.85	0.81	1.13	1.00
	Spring	132	−3.94	2.88	4.88	0.86	0.92	5.65
Bangalore (2000−2007)	Annual	1733	−7.05	4.28	8.24	0.89	1.06	5.55
	Winter	675	−5.72	3.79	6.87	0.88	1.05	4.83
	Summer	366	−8.48	4.36	9.54	0.69	0.90	11.62
	Monsoon	485	−7.97	4.66	9.23	0.59	0.87	12.45
	Spring	207	−6.68	3.25	7.43	0.83	0.98	7.01

[a]Water vapor is integrated precipitable water vapor. Time was collocated by same hour, daily data.

show systematic bias, with RMSE 3.48 mm at Gaize and 2.93 mm at Naqu.

3.2.1. GPS and MODIS NIR Clear Column Water Vapor

[16] MODIS NIR clear column water vapor show good correlation (R^2 0.91, N = 977 pairs) with corresponding GPS estimates over Kanpur for period 2004–2007, with RMSE 9.37 mm (Figure 2a and Table 3). MODIS product shows bias of −6.58 mm (overestimation) during this period. We have observed a large changes in bias with season that is −3.06, −7.84, −10.51, −4.02 (mm) during winter, summer, monsoon and spring seasons, respectively. The estimation of water vapor during summer and monsoon seasons shows larger RMSE of 11 and 12.87 mm, respectively. The daily bias, grouped as monthly and seasonal (Figure 3a) for Kanpur is found to be relatively higher bias (overestimation by MODIS) during summer and monsoon seasons (mostly 0 to −30 mm) compared to winter season (0 to −7 mm). It shows gradual increase in the overestimation by MODIS from 0−7 mm during winter to 0–30 mm during monsoon that further gradually decreases at the end of monsoon season. Most of the data show overestimation by MODIS during the entire year with large systematic changes in bias with month and season. Such seasonal behavior is also evident in the daily standard deviation of GPS and MODIS water vapor estimates (Figures 4a and 4b) that is gradually found to increase during summer and monsoon seasons. The standard deviation of MODIS data is found to be normally 1–2 mm during winter season, showing large fluctuations during summer and monsoon seasons (mostly 0–5 mm). Increase in error and bias during summer and monsoon seasons is reflected in monthly correlation values. A sharp decline in R^2 (∼0.25–0.3) is observed during June–July (Figure 5a, Kanpur).

[17] Similar behavior is observed over Hyderabad and Bangalore stations which show R^2 0.93, 0.89, respectively. The MODIS estimates (Table 3) show higher bias (overestimation), and RMSE during summer and monsoon seasons compared to the winter season. Figures 3 and 4 show daily variability of bias and standard deviation grouped as month and season over these stations. The meteorology of southern stations (Hyderabad and Bangalore) differs from Kanpur and shows relatively lower column water vapor throughout the year and monsoon season. The contrast in the seasons, such as temperature, rainfall, humidity, and wind field, is less over the southern stations and therefore, we observe gradually less fluctuations of bias and RMSE over stations that are in the south. The natures of systematic variation in bias, standard deviation (month-to-month and seasonal) for all the three stations are found to be similar (Figures 3, 4, and 5).

3.2.2. GPS and MODIS Infrared Water Vapor

[18] The GPS and MODIS Infrared channel water vapor show R^2 0.82, 0.84, 0.82 over Kanpur, Hyderabad and Bangalore, respectively (Figure 2b). The R^2 is found to be relatively lower over all three stations compared to MODIS NIR clear column (Tables 3 and 4). The systematic variations of daily bias (GPS-MODIS) of IR channel water vapor from January to December is similar to NIR clear column over three stations. However, the range of bias, as observed in Figure 3b, for IR channel water vapor is found to be more compared to NIR channel clear column (Figure 3a). The bias (overestimation) in MODIS IR channel water vapor over Kanpur is about 0 to −10 mm during winter season that increases to mostly 0 to −20 mm during summer and monsoon seasons (Figure 3b). The bias is found to be mostly negative (overestimation by MODIS) for both wet and dry seasons. The standard deviation of IR channel water vapor is found to be relatively higher compared to NIR Clear column (Figures 4a and 4b). The monthly correlation (R^2) is relatively low for IR water vapor compared to NIR clear column water vapor, although nature of month-to-month and seasonal variations is found to be similar (Figures 5a and 5b). The statistical comparison (Tables 3 and 4 and Figures 5a and 5b) of MODIS NIR clear column and IR channel water vapor with GPS water vapor clearly show that NIR Clear column product gives a better estimate of column water vapor. This could be attributed to the fact

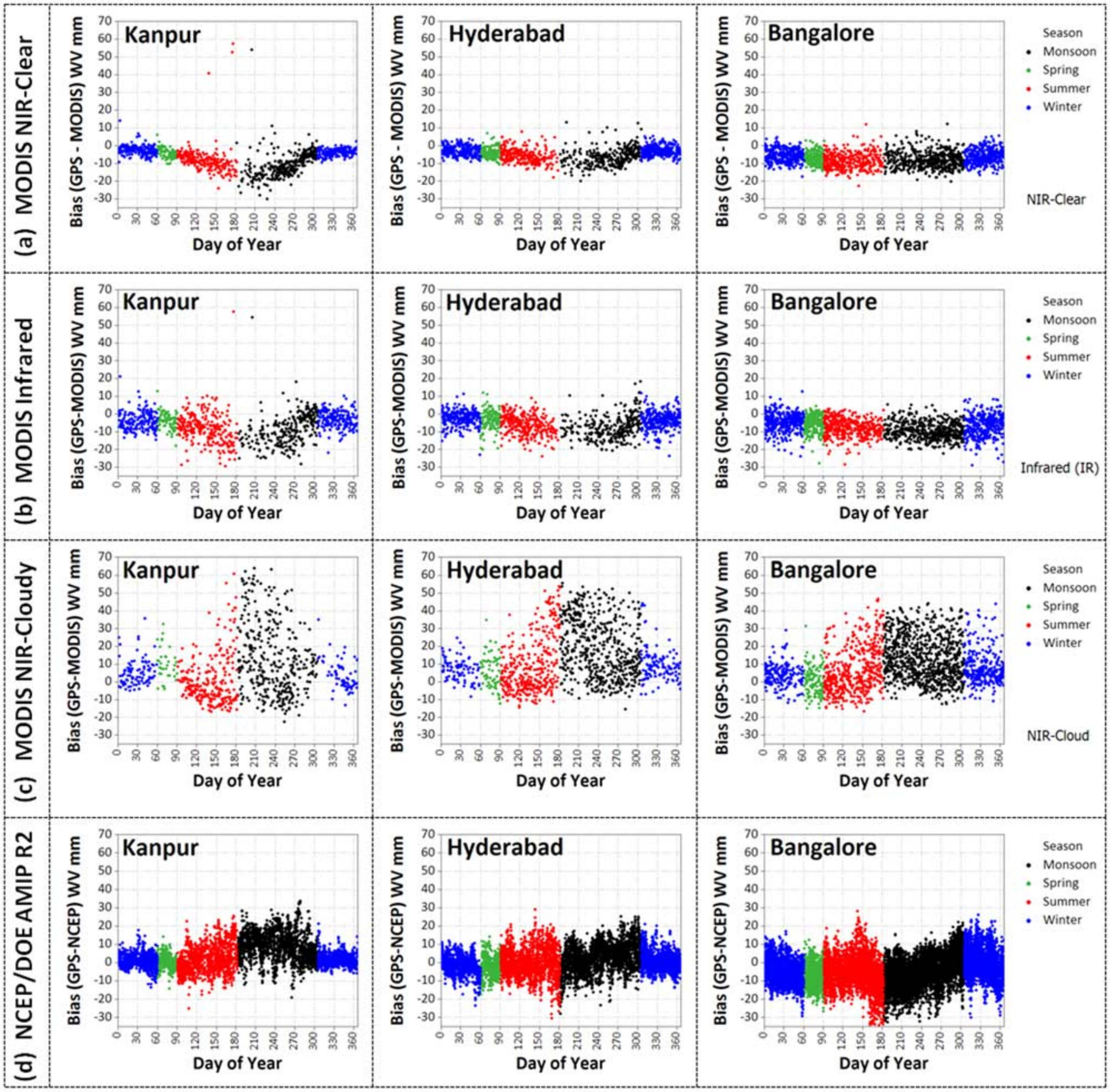

Figure 3. The bias between pairs: (a) GPS-MODIS NIR clear column, (b) GPS-MODIS Infrared, (c) GPS-MODIS NIR cloudy column, and (d) GPS-NCEP/DOE AMIP Reanalysis-2 6-hourly water vapor, over Kanpur (2004–2007), Hyderabad (2002–2007), and Bangalore (1996–2007) stations in India.

the MODIS NIR clear column (CC) product is a clear column (cloud free) estimate compared to MODIS IR product.

[19] The data points shown in Figures 2a and 6a are all tightly clustered around straight lines. This indicate that the MODIS near-IR channels are excellent for remote sensing of water vapor from space, although the present MODIS NIR clear water vapor values are biased in comparison with the GPS data. The bias, in principle, can be easily corrected. The data points in Figures 2b, 6b, 7a, and 7b are relatively loosely clustered around straight lines. The spread of the data points from the straight lines is found to be large, which shows that the IR technique is not as reliable as the NIR technique for estimation of total column water vapor amount. IR channels are intrinsically sensitive to atmospheric temperatures, and not as sensitive to atmospheric water vapor amounts (in comparison with the NIR channels).

3.2.3. GPS and MODIS NIR Cloudy Column Water Vapor

[20] The GPS and MODIS NIR Cloudy column water vapor show very poor correlation (R^2 0.33, 0.04, 0.10 over Kanpur, Hyderabad and Bangalore, respectively). The MODIS cloudy column water vapor shows no correlation

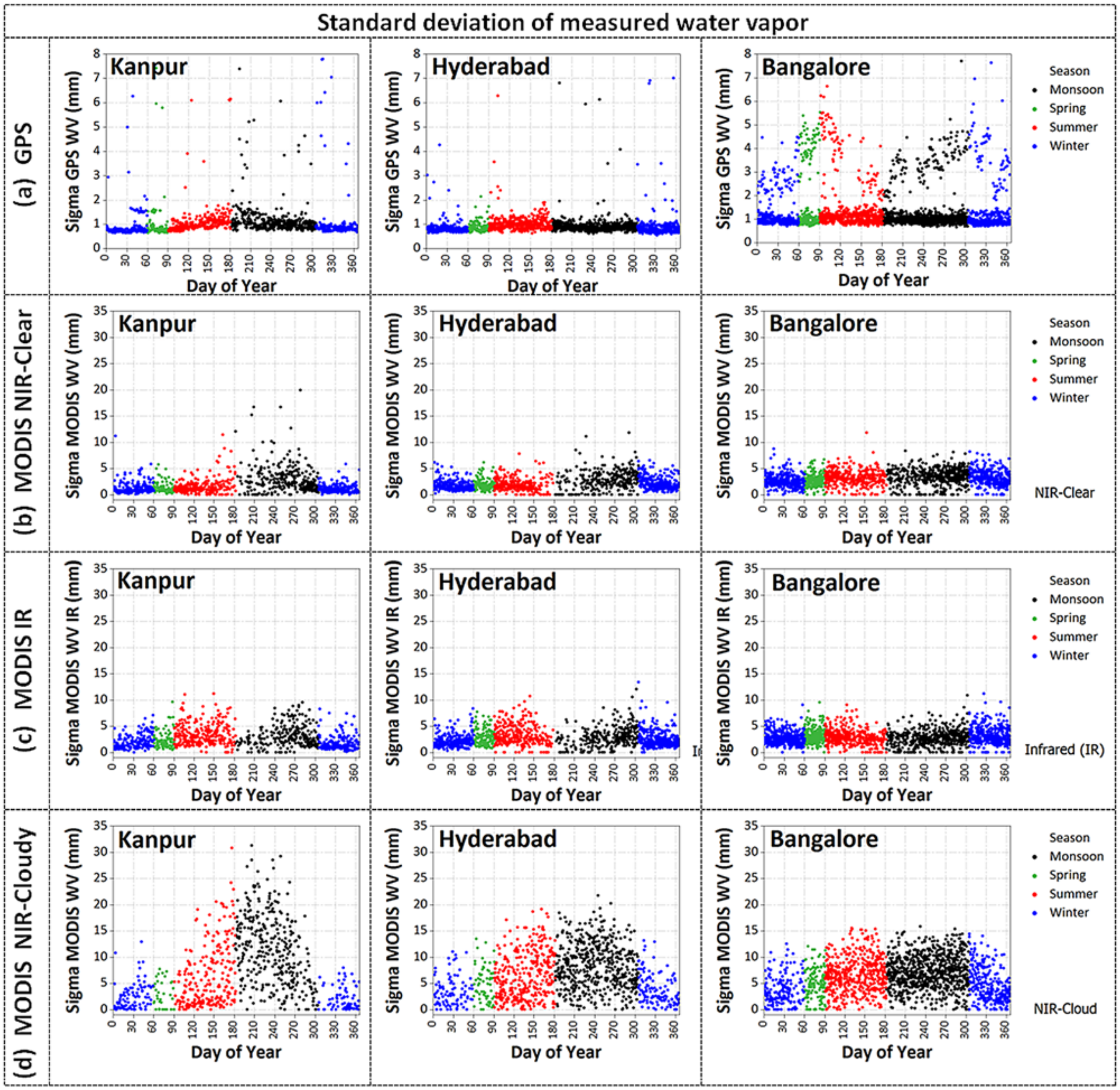

Figure 4. The standard deviation of water vapor estimation by (a) GPS, (b) MODIS NIR clear column, (c) MODIS IR, and (d) MODIS NIR cloudy column over Kanpur (2004–2007), Hyderabad (2002–2007), and Bangalore (2000–2007) stations in India.

especially during summer and monsoon season (Figure 2c). The MODIS cloudy column water vapor shows very large bias, standard deviation (GPS-MODIS) especially during summer and monsoon seasons (Table 5). The daily variations of bias show very large values: ±20 mm during summer and −10 to +60 mm during monsoon season over Kanpur. Similarly, very large bias is observed over Hyderabad and Bangalore especially during wet and cloudy days (Figure 3c). The magnitude of daily bias, shown month to month and grouped as season, show almost no agreement between GPS and MODIS estimates. Figure 5c shows no correlation between GPS and MODIS cloudy column water vapor and unacceptable R^2, bias and RMSE from January to December. The seasonal statistics shown in Table 5 and Figures 2c, 3c, 4c, and 5c clearly show that the MODIS derived cloudy column water vapor amounts are not reliable measures of the total vertical column water vapor amounts from ground to space during the cloudy conditions. It can be now concluded that the GPS senses the whole atmosphere while the MODIS NIR cloudy column reports only the water vapor amount above the cloud layer as the clouds obstruct view of atmosphere below them. As many MODIS channels saturate over the bright clouds, the MODIS NIR cloudy column product is intrinsically a less reliable product

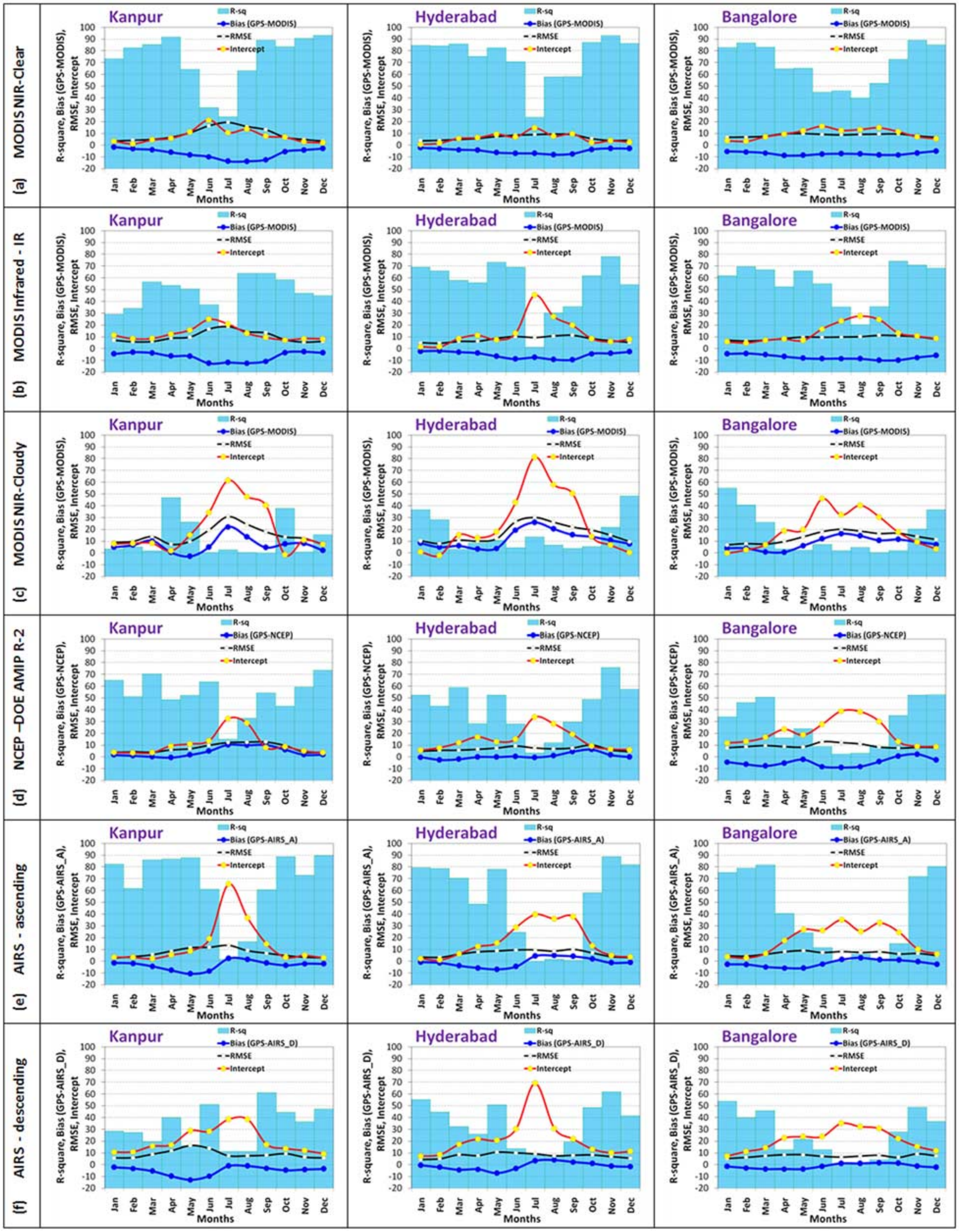

Figure 5. The monthly validation statistics (with GPS water vapor) for (a) MODIS NIR clear column, (b) MODIS IR, (c) MODIS NIR cloudy column, (d) NCEP/DOE AMIP Reanalysis-2, (e) AIRS ascending mode (daytime), and (f) AIRS descending (nighttime) over Kanpur, Hyderabad, and Bangalore stations in India.

Table 4. Seasonal Statistics and Correlations Between the Water Vapor Simultaneously Measured by GPS and MODIS Infrared at the Kanpur, Hyderabad, and Bangalore Stations[a]

Station (Period)	Season	Number of Pairs	Bias (GPS − MODIS) (mm)	Standard Deviation (mm)	RMSE (mm)	Linear Regression (GPS and MODIS Infrared)		
						R^2	Slope	Intercept
Kanpur (2004–2007)	Annual	991	−6.10	7.56	9.72	0.82	1.10	3.69
	Winter	365	−3.50	4.88	6.01	0.40	0.61	9.11
	Summer	274	−8.11	8.38	11.66	0.64	0.90	10.83
	Monsoon	268	−8.31	9.01	12.25	0.81	1.18	1.56
	Spring	84	−3.78	4.60	5.95	0.57	0.72	8.52
Hyderabad (2002–2007)	Annual	1278	−4.55	5.70	7.29	0.84	1.09	2.28
	Winter	556	−2.89	4.64	5.46	0.72	0.94	3.97
	Summer	304	−5.92	5.48	8.07	0.74	0.99	6.08
	Monsoon	279	−7.08	6.74	9.77	0.65	1.01	6.72
	Spring	139	−3.10	5.16	6.02	0.58	0.76	8.32
Bangalore (2000–2007)	Annual	1846	−7.04	5.48	8.92	0.82	1.06	5.44
	Winter	734	−5.58	5.72	8.00	0.73	0.95	6.43
	Summer	388	−7.69	4.97	9.16	0.69	1.03	6.87
	Monsoon	502	−9.43	4.82	10.60	0.52	0.74	18.68
	Spring	222	−5.26	4.72	7.06	0.67	0.91	6.95

[a]Water vapor is integrated precipitable water vapor. Time was collocated by same hour, daily data.

for column water vapor. Thus, the poor or no correlation of NIR cloudy column with GPS water vapor is anticipated and suggests use of other products for column water vapor estimates.

3.3. GPS and NCEP/DOE AMIP-II Reanalysis-2 Water Vapor

[21] The GPS and NCEP/DOE AMIP-II Reanalysis-2 derived water vapor show good to moderate correlation (R^2 0.87, 0.77 and 0.60 over Kanpur, Hyderabad and Bangalore, respectively). The NCEP/DOE AMIP-II data is available at grid resolution of 2.5°. Therefore, the increasing distance of the GPS station from the center of the grid increases mismatch of spatial collocation of both (GPS and NCEP/DOE AMIP-II) data. The Hyderabad and Bangalore show poor spatial collocation (GPS and NCEP/DOE AMIP-II), a good spatial collocation is required for a better correlation. This causes decrease in correlation (Table 6) over Hyderabad, Bangalore compared to Kanpur since the GPS and NCEP/DOE AMIP-II do not entirely represent the same sky and ground conditions (temperature and surface pressure). The comparison of NCEP/DOE AMIP-II 6-hourly values with corresponding GPS values (time collocated, by hour) shows moderate seasonal correlation over Kanpur station. Unlike MODIS Terra NIR and IR channel water vapor, the bias (GPS-NCEP/DOE AMIP-II) is found to be positive over Kanpur during monsoon season showing underestimation of column water vapor by NCEP/DOE AMIP-II during monsoon season (9.03 mm over Kanpur, Table 6). The GPS-NCEP/DOE AMIP-II standard deviation and RMSE is found to be higher during summer and monsoon seasons with maximum value during monsoon season (Table 6). The individual pairs of GPS-NCEP/DOE AMIP-II water vapor show gradual increase in underestimation by NCEP/DOE AMIP-II from summer to monsoon season. The end of summer season (June) and beginning of

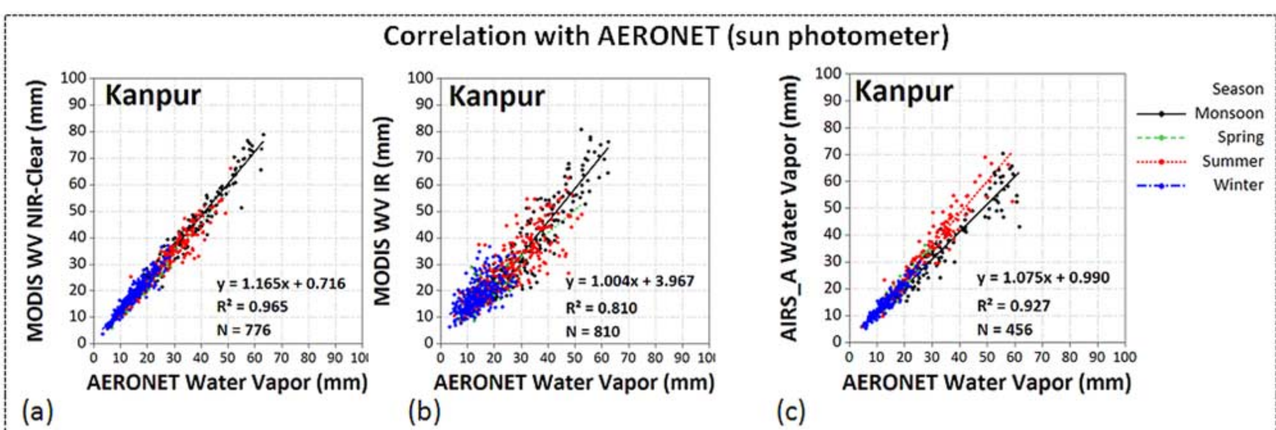

Figure 6. The correlation between water vapor from (a) daily MODIS NIR clear column and AERONET (2001–2007), (b) daily MODIS Infrared (IR) column and AERONET (2001–2007), and (c) daily AIRS_A (ascending mode, daytime) and AERONET (2002–2007) over Kanpur station.

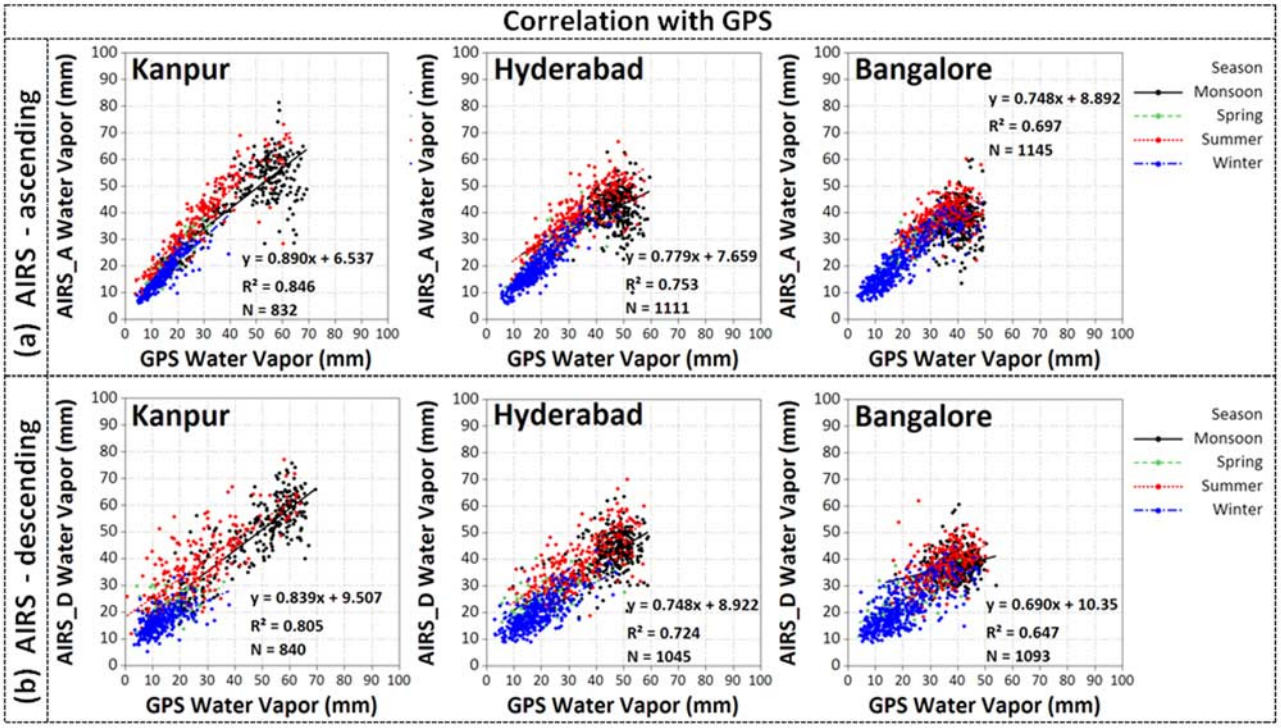

Figure 7. The correlation between water vapor from (a) daily AIRS_A (ascending mode, daytime) and GPS and (b) daily AIRS_D (descending mode, nighttime) and GPS, over Kanpur (2004–2007), Hyderabad (2002–2007), and Bangalore (2002–2007) stations in India.

monsoon season (July–August) over Kanpur show mostly underestimation by NCEP/DOE AMIP-II by 0–25 mm (Figure 3d). The other months show both underestimation and overestimation by ±10 mm.

[22] The GPS-NCEP (NCEP/NCAR Reanalysis 1) shows common bias of 2.0 mm and standard deviation of 4.0 and 5 mm over Bangalore and Hyderabad, respectively [*Jade and Vijayan*, 2008]. The bias is found to be around 5.6 mm with standard deviation of 7.0 mm over Lucknow (70 km northeast of Kanpur) [*Jade and Vijayan*, 2008]. The bias was around 0.2–5 mm with standard deviation 5–7 mm for most of the stations such as Bhopal, Jabalpur, Bhubaneshwar, etc., while it varies to relatively large bias of 21 mm and standard deviation of 21 mm over southern station Kodaikanal and some northeast stations in India [*Jade and Vijayan*, 2008].

[23] The range of bias in NCEP/DOE AMIP-II water vapor is much larger compared to MODIS NIR clear column water vapor (Figures 3a and 3d). The monthly

Table 5. Seasonal Statistics and Correlations Between the Water Vapor Simultaneously Measured by GPS and MODIS NIR Cloudy Column at the Kanpur, Hyderabad, and Bangalore Stations[a]

Station (Period)	Season	Number of Pairs	Bias (GPS − MODIS) (mm)	Standard Deviation (mm)	RMSE (mm)	Linear Regression (GPS and MODIS NIR Cloudy) R^2	Slope	Intercept
Kanpur (2004–2007)	Annual	790	7.29	16.60	18.13	0.33	0.57	8.49
	Winter	162	4.84	7.74	9.13	0.07	0.23	7.94
	Summer	249	1.00	13.76	13.79	0.21	0.45	16.32
	Monsoon	345	12.67	19.96	23.64	0.03	0.25	25.56
	Spring	34	10.47	9.04	13.83	0.02	0.14	8.25
Hyderabad (2002–2007)	Annual	1145	13.41	15.42	20.43	0.04	0.22	15.87
	Winter	206	8.47	8.01	11.66	0.33	0.52	3.23
	Summer	349	9.09	15.62	18.07	0.00	0.00	26.69
	Monsoon	527	19.09	16.11	24.98	0.01	−0.16	33.64
	Spring	63	5.96	9.12	10.89	0.03	0.25	15.23
Bangalore (2000–2007)	Annual	1928	9.00	11.94	14.95	0.10	0.34	11.87
	Winter	474	6.64	8.65	10.90	0.37	0.51	4.57
	Summer	489	6.36	12.72	14.22	0.00	0.02	25.58
	Monsoon	833	13.19	12.17	17.95	0.00	−0.09	27.58
	Spring	132	0.80	7.53	7.57	0.26	0.66	6.86

[a]Water vapor is integrated precipitable water vapor. Time was collocated by same hour, daily data.

Table 6. Seasonal Statistics and Correlations Between the Water Vapor Simultaneously Obtained From GPS and NCEP/DOE AMIP Reanalysis-2 at the Kanpur, Hyderabad, and Bangalore Stations[a]

Station (Period)	Season	Number of Pairs	Bias (GPS − NCEP) (mm)	Standard Deviation (mm)	RMSE (mm)	Linear Regression (GPS and NCEP) R^2	Slope	Intercept
Kanpur (2004–2007)	Annual	4765	4.20	7.26	8.39	0.87	0.72	3.84
	Winter	1495	1.55	3.68	3.99	0.60	0.63	3.65
	Summer	1222	1.88	7.42	7.65	0.76	0.63	8.15
	Monsoon	1700	9.03	7.52	11.75	0.80	0.73	2.95
	Spring	348	0.07	3.88	3.88	0.70	0.79	3.40
Hyderabad (2002–2007)	Annual	6821	0.67	6.94	6.97	0.77	0.81	5.23
	Winter	2288	−0.25	5.19	5.20	0.60	0.65	6.84
	Summer	1614	−0.07	7.79	7.79	0.58	0.73	9.49
	Monsoon	2351	2.73	7.61	8.09	0.47	0.80	6.03
	Spring	568	−2.06	5.22	5.61	0.59	0.55	11.86
Bangalore (1996–2007)	Annual	14824	−4.62	8.08	9.30	0.60	0.82	9.70
	Winter	5097	−2.82	7.54	8.05	0.48	0.56	11.47
	Summer	3224	−5.38	8.62	10.16	0.32	0.68	15.54
	Monsoon	5190	−5.11	8.39	9.82	0.16	0.56	21.81
	Spring	1313	−7.80	5.48	9.53	0.51	0.54	16.48

[a]Water vapor is integrated precipitable water vapor. Time was collocated by same hour, 6-hourly data.

correlation, bias, and RMSE of GPS and NCEP/DOE AMIP-II Reanalysis-2 water vapor (Figure 5d) show lowest correlation in the beginning of monsoon season (July) like MODIS NIR Clear column water vapor. The statistical comparison of multiple MODIS water vapor products and NCEP/DOE AMIP-II data clearly show low correlation, high bias and RMSE during the monsoon season (Figure 5).

3.4. GPS and AIRS Water Vapor

3.4.1. GPS and AIRS (Daytime) Water Vapor

[24] The GPS and AIRS (ascending mode, daytime) derived water vapor over Kanpur show moderate (R^2 ~0.85 for N = 832 pairs) correlation during 2004–2007 with RMSE 7.81 mm (Figure 7a and Table 7). The value of R^2 over Hyderabad and Bangalore, for 2002–2007, is found to be 0.75 and 0.70, respectively. The AIRS data show negative bias (GPS-AIRS) during summer and positive bias during monsoon over Hyderabad and Bangalore (Table 7). The standard deviation and RMSE is found to be higher during summer and monsoon seasons compared to winter or spring season (Table 7). The daily bias is systematic and range 0 to −20 mm (negative bias) over Kanpur during summer season implying overestimation by AIRS (Figure 8). The bias over Kanpur is either positive or negative (range mostly −20 to 20 mm) during the monsoon season. Large positive bias (up to 35 mm) during onset of monsoon season in July implies underestimation by AIRS during cloudy sky conditions (Figure 8). This is in agreement with the observation of *Raja et al.* [2008], who have found changes in the bias (GPS-AIRS) with season over the United States, increasing from small negative values in April to peak positive values in July and decreasing thereafter. The bias is mostly negative and relatively low (0 to −10 mm) during end of monsoon season with mostly clear-sky days. The bias over Kanpur is found to be a relatively low ±5 mm during November–December (winter season). The standard deviation of daily estimations of water vapor by AIRS shows large variation (mostly 0–10 mm) during monsoon season with maximum cloudy sky days (Figure 8c). Otherwise, the standard deviation is mostly 0–3 mm over Kanpur. Similarly, Hyderabad and Bangalore show large underestimation by AIRS, and relatively larger standard deviation during cloudy sky days (Figures 8a and 8c). The monthly correlation over all the three stations (Figure 5e) shows no correlation during July and August (monsoon season) owing to cloudy conditions. The AIRS daytime water vapor estimations appear to be highly underestimating during cloudy sky days while overestimating during clear-sky days (Figures 5, 8a, and 8c). *Raja et al.* [2008] have also found seasonal dependency of bias; AIRS water vapor estimates tend to be relatively dry in moist atmospheres (>40 mm) and wet in dry cases (<10 mm) over the United States. The observed bias (GPS-AIRS) may be partially explained by surface pressure differences [*Raja et al.*, 2008]. Our analysis during 2002–2007 shows dry bias (underestimation) for monsoon months (wet season) and wet bias (overestimation) for dry months (Figures 8a and 8b).

3.4.2. GPS and AIRS (Nighttime) Water Vapor

[25] The GPS and AIRS (descending mode, nighttime) derived water vapor over Kanpur show moderate correlation (R^2 ~0.81 for N = 840 pairs) for period 2004–2007 with RMSE 9.59 mm (Figure 7b and Table 8). The value of R^2 over Hyderabad and Bangalore, for period 2002–2007, is found to be 0.72 and 0.65, respectively; this is a lower value compared to daytime water vapor from AIRS (Tables 7 and 8). The GPS-AIRS nighttime water vapor RMSE, standard deviation is found to be higher during summer and monsoon seasons like daytime AIRS. The AIRS nighttime also show increase in overestimation from winter (bias, 0 to −10 mm) to summer season (bias, 0 to −30 mm) while under estimate by mostly 0–10 mm during cloudy sky days in the monsoon season (Figure 8b). The nighttime AIRS bias shows more scatter and range compared to daytime estimates of water vapor. The standard deviation of AIRS nighttime water vapor estimates is mostly 0–2 mm while large values (mostly 0–10 mm) are observed during summer and monsoon seasons (Figure 8d). The monthly R^2 of nighttime AIRS and GPS water vapor is found to be low

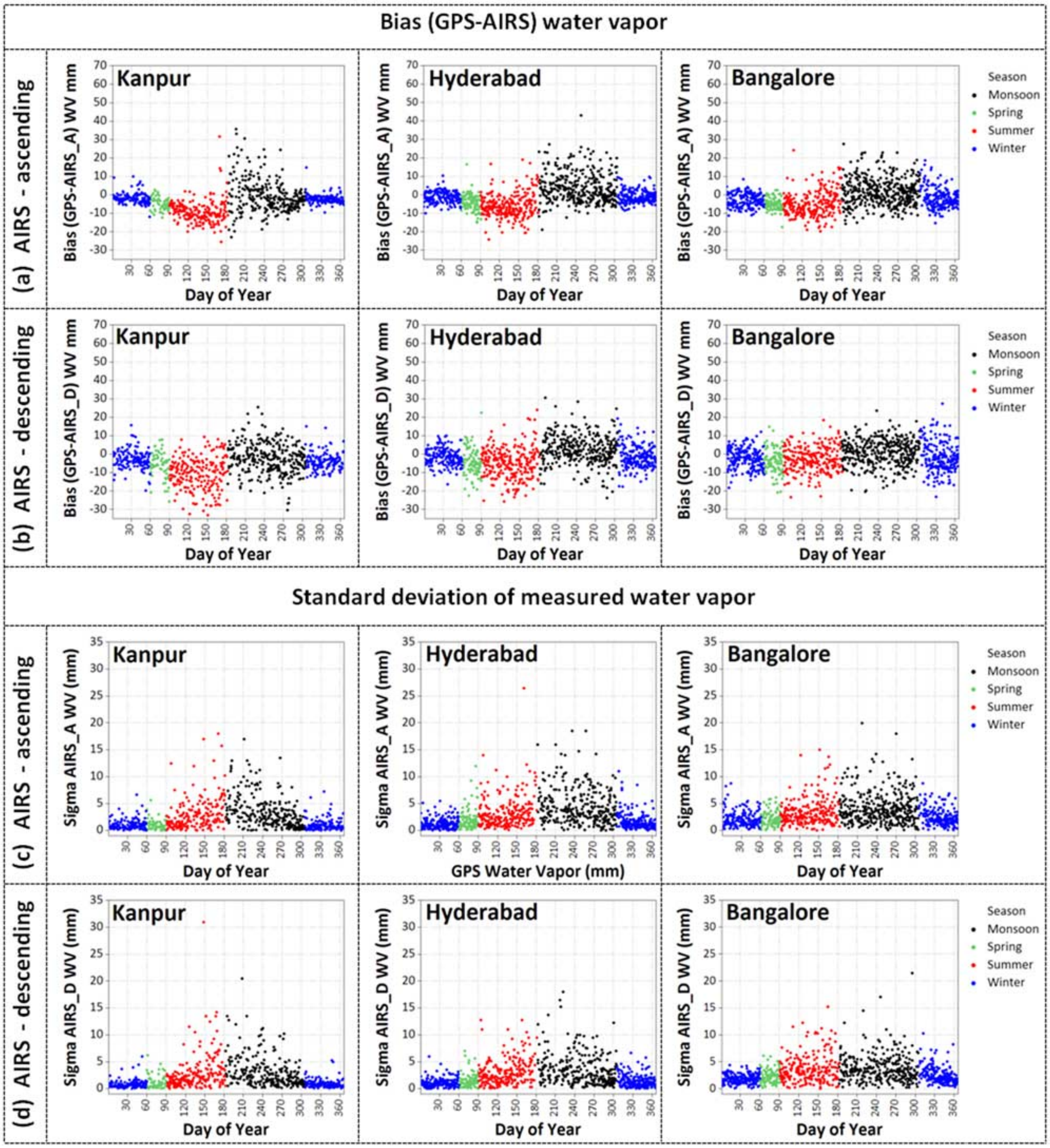

Figure 8. The bias between pairs: (a) GPS-AIRS ascending or daytime water vapor and (b) GPS-AIRS descending or nighttime water vapor over Kanpur (2004–2007), Hyderabad (2002–2007), and Bangalore (2002–2007) stations. The standard deviation of water vapor estimation by (c) AIRS daytime and (d) AIRS nighttime over three stations.

Table 7. Seasonal Statistics and Correlations Between the Water Vapor Simultaneously Obtained From GPS and AIRS_A (Ascending Mode, Daytime) at the Kanpur, Hyderabad, and Bangalore Stations[a]

Station (Period)	Season	Number of Pairs	Bias (GPS − AIRS_A) (mm)	Standard Deviation (mm)	RMSE (mm)	Linear Regression (GPS and AIRS_A) R^2	Slope	Intercept
Kanpur (2004–2007)	Annual	832	−3.38	7.04	7.81	0.85	0.89	6.54
	Winter	270	−1.97	2.69	3.33	0.79	0.91	3.30
	Summer	208	−8.88	5.93	10.68	0.83	0.95	10.29
	Monsoon	291	−0.54	8.71	8.73	0.72	0.76	11.24
	Spring	63	−4.46	3.32	5.56	0.86	1.14	2.07
Hyderabad (2002–2007)	Annual	1111	−0.92	7.03	7.09	0.75	0.78	7.66
	Winter	384	−1.21	3.16	3.39	0.84	0.88	3.40
	Summer	264	−5.87	6.37	8.66	0.66	0.73	14.97
	Monsoon	366	3.75	7.96	8.80	0.30	0.51	18.03
	Spring	97	−3.91	4.42	5.90	0.71	0.90	6.15
Bangalore (2002–2007)	Annual	1145	−1.60	6.61	6.80	0.70	0.75	8.89
	Winter	385	−2.16	4.67	5.14	0.78	0.77	6.45
	Summer	252	−4.65	6.67	8.13	0.35	0.51	20.86
	Monsoon	411	1.58	7.29	7.46	0.04	0.22	28.41
	Spring	97	−4.86	3.18	5.81	0.82	0.92	6.49

[a]Water vapor is integrated precipitable water vapor. Time was collocated by same hour, daytime daily data.

compared to daytime AIRS and GPS (Figures 5e and 5f). The observed correlation is found to be absent during monsoon months (July–August) over all three stations. AIRS nighttime water vapor estimates show similar seasonal behavior (overestimation or underestimation) compared to daytime estimates. However, nighttime estimates of water vapor from AIRS are found to be poor compared to AIRS daytime estimates. MODIS NIR clear column gives better estimates of water vapor compared to AIRS daytime or nighttime.

[26] The AIRS column water vapor product used in this study uses a combination of data from microwave and infrared channels to compute total water vapor. The microwave-only retrievals from AIRS show slight cloud-dependent bias compared to full retrievals from AIRS that utilizes both infrared and microwave radiances. The bias increases with increasing cloud fraction. This cloud-dependent bias in the microwave-only retrieval is attributed to the contributions from cloud and other cloud-related parameters, such as cloud amount, surface wind and precipitation. The AIRS algorithm uses full retrieval for clear case and microwave only for retrieval for cloudier conditions [*Susskind et al.*, 2003]. The retrieval error, partially, is also likely due to slight miscalibration of AMSU. *Fetzer et al.* [2005] have observed that the absolute difference between AIRS and AMSR-E (Advanced Microwave Scanning Radiometer–EOS, on board Aqua) derived total water vapor show appreciable bias of 0.5 mm during nighttime with no bias during daytime observations. The daytime and nighttime difference is attributed to increased stratus cloud at night which is known to affect the AIRS retrievals [*Fetzer et al.*, 2005]. Further, the AIRS temperature profile data show that AIRS cannot fully resolve the tropopause [*Gettelman et al.*, 2004]. The decrease in correlation between nighttime GPS-AIRS water vapor compared to the daytime GPS-AIRS (Figure 7 and Tables 7 and 8) is therefore anticipated.

3.5. AERONET and MODIS Water Vapor

3.5.1. AERONET and MODIS NIR Clear Column Water Vapor

[27] AERONET and MODIS NIR Clear column water vapor show good correlation (R^2 = 0.97, RMSE 5.44 mm, N = 776 pairs) over Kanpur (Figure 6a and Table 9). The

Table 8. Seasonal Statistics and Correlations Between the Water Vapor Simultaneously Obtained From GPS and AIRS_D (Descending Mode, Nighttime) at the Kanpur, Hyderabad, and Bangalore Stations[a]

Station (Period)	Season	Number of Pairs	Bias (GPS − AIRS_D) (mm)	Standard Deviation (mm)	RMSE (mm)	Linear Regression (GPS and AIRS_D) R^2	Slope	Intercept
Kanpur (2004–2007)	Annual	840	−5.02	8.17	9.59	0.81	0.84	9.51
	Winter	268	−3.37	4.86	5.92	0.35	0.46	10.51
	Summer	216	−10.76	8.95	14.00	0.64	0.72	18.31
	Monsoon	293	−2.20	8.13	8.43	0.77	0.78	11.80
	Spring	63	−5.52	6.89	8.83	0.20	0.39	15.63
Hyderabad (2002–2007)	Annual	1045	−1.36	7.61	7.73	0.72	0.75	8.92
	Winter	370	−1.51	5.27	5.49	0.53	0.55	9.40
	Summer	252	−4.98	8.12	9.52	0.52	0.62	17.69
	Monsoon	327	2.49	7.78	8.17	0.41	0.60	15.15
	Spring	96	−4.41	7.21	8.45	0.32	0.40	17.18
Bangalore (2002–2007)	Annual	1093	−1.30	7.16	7.27	0.65	0.69	10.35
	Winter	392	−1.97	6.84	7.12	0.54	0.57	10.37
	Summer	238	−3.02	7.35	7.94	0.28	0.51	19.93
	Monsoon	366	1.18	6.85	6.95	0.08	0.25	27.98
	Spring	97	−3.81	6.42	7.46	0.46	0.51	14.14

[a]Water vapor is integrated precipitable water vapor. Time was collocated by same hour, nighttime daily data.

Table 9. Seasonal Statistics and Correlations Between the Water Vapor Simultaneously Measured by AERONET Sun Photometer and MODIS NIR Clear Column at the Kanpur Station, 2001–2007[a]

Season	Number of Pairs	Bias (AERONET − MODIS) (mm)	Standard Deviation (mm)	RMSE (mm)	Linear Regression (AERONET and MODIS NIR)		
					R^2	Slope	Intercept
Annual	776	−4.36	3.26	5.44	0.97	1.17	0.72
Winter	289	−3.61	2.03	4.14	0.91	1.14	1.65
Summer	216	−4.17	3.13	5.21	0.94	1.12	1.22
Monsoon	184	−6.82	4.09	7.95	0.96	1.21	−0.18
Spring	87	−2.11	1.44	2.56	0.97	1.12	0.16

[a]Water vapor is integrated precipitable water vapor. Time was collocated by same hour, daily data.

bias (AERONET-MODIS) is about −3.61, −4.17, −6.82, and −2.11 mm during winter, summer, monsoon and spring seasons, respectively. The RMSE is found to be relatively higher (7.95 mm) during the monsoon season. MODIS NIR clear column water vapor shows good agreement with AERONET similar to GPS estimates.

3.5.2. AERONET and MODIS Infrared Water Vapor

[28] AERONET and MODIS infrared column water vapor show relatively moderate correlation (R^2 0.81, N = 810 pairs) and higher RMSE 7.17 mm over Kanpur (Figure 6a and Table 10). The bias (AERONET-MODIS) is found to be −4.39, −3.86, −4.53, and −2.67 mm during winter, summer, monsoon and spring seasons, respectively. The RMSE is found to be relatively higher (8.43 mm) during the monsoon season (Table 10). On comparison with the AERONET, MODIS NIR channel (clear column) gives better estimates compared to infrared channel derived water vapor.

3.6. AERONET and AIRS (Daytime) Water Vapor

[29] Only daytime AIRS estimates can be compared directly with AERONET as AERONET Sun photometer operates during daytime only. AIRS (in an ascending mode: daytime) passes over the study region at approximately 1330–1430 LT (afternoon) and is found to show good correlation (R^2 0.92) with corresponding AERONET estimates (Figure 6c). The bias (AERONET-AIRS) is found to be −1.68, −5.77, −1.09, and −2.81 mm during winter, summer, monsoon and spring seasons, respectively. AIRS daytime water vapor estimates show good agreement with AERONET derived water vapor during clear-sky days (Table 11).

4. Conclusions

[30] The GPS and AERONET can be used as a validation tool for satellite and model-based water vapor retrievals. The validation and estimation of seasonal bias of 1° gridded products (MODIS, AIRS) are important as they are used for assimilation into numerical weather prediction and global climate models. The seasonal dependency is evident in bias and RMSE differences, where the effect of moist or wet atmospheric conditions and the effect of cloudy days are visible. The results can be used for partial bias correction where systematic overestimation or underestimation is common. The satellite retrieval of water vapor during monsoon season (wet months), especially during cloudy days, needs relatively large bias correction. MODIS NIR cloudy column water vapor gives unacceptable estimates (no correlation with GPS) and is not good for cloud water vapor studies. Microwave data may provide better estimates of water vapor under cloudy conditions [*Mattioli et al.*, 2005; *van Baelen et al.*, 2005]. MODIS IR water vapor and AIRS water vapor product can be further improved by taking into account systematic and relatively large day-to-day bias correction. The MODIS NIR clear column water vapor product is more reliable compared to other satellite data sets used in the present study over India. The MODIS NIR clear column and IR water vapor show overestimation (negative bias) compared to GPS estimates for both dry and wet months. The magnitude of bias is more during summer and monsoon months. Whereas NCEP/DOE AMIP-II Reanalysis-2 water vapor over Kanpur show large positive bias (underestimation) during monsoon season. *Jade and Vijayan* [2008] show bias (GPS-NCEP/NACR Reanalysis) range of 0.2–21 and standard deviation of 5–21 mm over GPS stations in India with conspicuously higher values over hilly regions. AIRS daytime and nighttime data show mostly negative bias (overestimation) during summer months and variable bias during monsoon months. The AIRS show positive bias (underestimation) due to effect of cloudy sky conditions. The magnitude of bias is more in nighttime retrievals compared to daytime estimates by AIRS. The AERONET and MODIS Terra clear column water vapor (before noon) and AERONET and

Table 10. Seasonal Statistics and Correlations Between the Water Vapor Simultaneously Measured by AERONET Sun Photometer and MODIS (Infrared) at the Kanpur Station, 2001–2007[a]

Season	Number of Pairs	Bias (AERONET − MODIS) (mm)	Standard Deviation (mm)	RMSE (mm)	Linear Regression (AERONET and MODIS IR)		
					R^2	Slope	Intercept
Annual	810	−4.08	5.89	7.17	0.81	1.00	3.97
Winter	289	−4.39	4.66	6.41	0.40	0.68	8.92
Summer	246	−3.86	6.55	7.61	0.67	0.85	7.82
Monsoon	188	−4.53	7.11	8.43	0.86	1.25	−3.76
Spring	87	−2.67	4.30	5.06	0.59	0.77	6.49

[a]Water vapor is integrated precipitable water vapor. Time was collocated by same hour, daily data.

Table 11. Seasonal Statistics and Correlations Between the Water Vapor Simultaneously Measured by AERONET Sun Photometer and AIRS_A (Ascending Mode, Daytime) at the Kanpur Station 2001–2007[a]

Season	Number of Pairs	Bias (AERONET – AIRS_A) (mm)	Standard Deviation (mm)	RMSE (mm)	Linear Regression (AERONET and AIRS_A)		
					R^2	Slope	Intercept
Annual	456	−2.79	4.03	4.90	0.93	1.08	0.99
Winter	171	−1.68	1.71	2.40	0.90	1.06	0.83
Summer	131	−5.77	4.51	7.32	0.92	1.21	−0.06
Monsoon	118	−1.09	4.43	4.56	0.91	1.03	0.10
Spring	36	−2.81	2.56	3.81	0.94	1.25	−1.74

[a]Water vapor is integrated precipitable water vapor. Time was collocated by same hour, daytime daily data.

AIRS Aqua daytime (afternoon) show good agreement (R^2 = 97% with RMSE 5.44 mm and R^2 = 93% with RMSE 4.90 mm, respectively). Slightly higher correlation of MODIS and AIRS water vapor with AERONET compared to GPS is because AERONET operates and measures water vapor during direct Sun vision and clear-sky conditions only. The present results will be of great help to satellite science teams to tune their algorithms for water vapor retrieval, especially over India.

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