

GPS and satellite meteorology for understanding monsoon dynamics over the Indian sub-continent

ANUP K. PRASAD¹, RAMESH P. SINGH^{1,2},
SHATRUGHAN SINGH¹ & DIP S. NANDA¹

¹ Department of Civil Engineering, Indian Institute of Technology, Kanpur 208016, India

² Centre for Earth Observing and Space Research, College of Science, George Mason University, Fairfax, USA

rsingh3@gmu.edu

Abstract Atmospheric water vapour plays a major role in the radiative balance of the Earth's atmosphere and influences the hydrological cycle. The total column of atmospheric water vapour, obtained from Global Positioning System (GPS) and Moderate Resolution Imaging Spectroradiometer (MODIS), is found to be very dynamic over the Indian sub-continent. Water vapour is found to be highly variable over the Indo-Gangetic (IG) plains, one of the agriculturally very productive regions in the world, where a strong coupling is found to exist between the land and atmosphere. Monthly and seasonal water vapour over northern India shows a large deficiency for the summer season during 2005, which was one of the warmest years compared to the year 2004. A deficiency in the GPS and MODIS water vapour (monsoon season) is also observed during the drought year of 2004 due to failure of the Indian monsoon in northern India compared to a normal monsoon rainfall year 2005. The water vapour variability and its spatio-temporal dynamics will be useful in understanding the dynamics of the Indian monsoon.

Key words water vapour; GPS; MODIS; TRMM; monsoon; rainfall; surface temperature

INTRODUCTION

Water vapour is one of the important constituents of the atmosphere; it affects the thermodynamics of the atmosphere and has an impact on climatic processes (Rocken *et al.*, 1993; Bevis *et al.*, 1994; Businger *et al.*, 1996; Duan *et al.*, 1996; Kay & Box, 2000). Global Positioning System (GPS) and satellite remote sensing have emerged as one of the reliable methods for water vapour estimation in the atmosphere (Bevis *et al.*, 1994; Businger *et al.*, 1996). A GPS provides estimates of the continuous (hourly average) total column of water vapour during all weather conditions, over ground-based stations, using very high-ultra high frequency (VHF-UHF) microwaves (0.1–3 GHz) from a constellation of GPS satellites. Now satellite data are capable of providing various atmospheric parameters over the globe. Yuan *et al.* (1993) discussed the role of GPS in sensing the effects of climate change. Recently, Jade *et al.* (2005) have shown the variability of GPS water vapour over Bangalore in southern India and Hanle in the northern Himalayan region.

Large deviations have been found in the trend of the Indian monsoon during the drought years 2002 and 2004. The increasing anthropogenic and industrial pollution is affecting the hydrological cycle (Ramanathan *et al.*, 2005). The effect of growing anthropogenic pollution, such as the formation of fog, which is partially dependent

upon the presence of moisture and temperature, is an annual event over the Indo-Gangetic (IG) plains during the winter season (December–January). We have undertaken study of GPS-determined water vapour along with satellite (Moderate Resolution Imaging Spectroradiometer, MODIS) derived water vapour, to study intra and inter-annual variability over the northern plains (Kanpur – iitk station) and southern parts (Hyderabad (hyde) and Bangalore (iisc)) of India during 2004 and 2005 (see Fig. 1). In this paper, we also explore the sensitivity of GPS towards various climatic processes and events such as hot temperatures, failure of the monsoon and formation of fog, etc. The role of GPS and satellite-derived meteorological parameters in understanding the dynamics of the monsoon and climatic conditions over the Indian sub-continent are discussed.

DATA USED

Satellite-emitted microwave signals from space to the ground GPS receiver are delayed due to the atmosphere (troposphere). The delay in the GPS signal induced by the troposphere, as measured by a ground receiver in two frequencies, consists of two parts: dry delay and wet delay. Wet delay is obtained as the difference between the total and dry delay (modelled using pressure data either from NCEP or a local barometer) (Rocken *et al.*, 1993; Bevis *et al.*, 1994; Duan *et al.*, 1996). We have processed GPS data, available in rinex format, for three stations over India to derive total column precipitable water vapour using GAMIT/GLOBK v10.21 software (<http://www-gpsg.mit.edu/~simon/gtgk/>) which is a standard processing tool for the retrieval of the WV column. The GPS data for Kanpur (iitk) was obtained from a Trimble Survey Grade Dual Frequency receiver (Trimble 5700 with Zephyr geodetic antenna, 1.2 and 1.5 GHz). GPS data for two permanent IGS (International GNSS Service) stations, Hyderabad (hyde) and Bangalore (iisc), are downloaded from sources provided by SOPAC (Scripps Orbit and Permanent Array Center, <http://sopac.ucsd.edu/>). The accuracy of GPS water vapour measurements partially depends on the accuracy of the surface pressure measurements. The NCEP estimates have been found to be within acceptable limits for GPS stations without local MET (meteorological) package except at high altitude stations where NCEP estimates are known to be less accurate (Quinn & Herring, 1996). For retrieval of water vapour, we have considered a regional network of GPS stations in GAMIT, including iitk, hyde, iisc, lhas, iitk, kit3, ntus, bako, kunm (<http://sopac.ucsd.edu/>). Daily rinex files, containing data at 30 second intervals, were processed using inbuilt Fortran script to obtain water vapour at 30 second intervals. We computed hourly average precipitable water vapour for the iitk, iisc and hyde stations, for further analysis. The accuracy of the GPS derived water vapour was found to be ~1–2 mm over Kanpur, Bangalore and Hyderabad.

MODIS Terra covers the globe every 1–2 days, providing data of moderate spatial resolution (250 m at nadir) with a wide swath (2330 km), and large spectral range (36 channels between 0.412 and 14.2 μm). We have used the Level-3 MODIS Terra (MOD08_M3, <http://modis-atmos.gsfc.nasa.gov/>) monthly global grid product (near-infrared water vapour with clear column (NIR CC)) available at a spatial resolution of 1 degree. MODIS water vapour is derived from channels in the near-infrared region

that are useful for remote sensing of water vapour (King *et al.*, 1992; Gao & Kaufman, 1998, 2003). MODIS water vapour estimation may have errors of up to 10% especially under hazy conditions as described by Gao & Kaufman (1998). The correlation between MODIS and GPS water vapour has been found to be greater than 0.95 (Tibet and Europe) (Li *et al.*, 2003; Liu *et al.*, 2006). The variability of MODIS water vapour has been compared with GPS derived water vapour over three Indian stations. We have also used monthly MODIS Terra land surface temperature (MOD11C, day time) that is available as a global grid with 0.05 degree spatial resolution.

The monthly rainfall product from the Tropical Rainfall Measuring Mission (TRMM) and another satellite (3B43 Version 6) was obtained from Goddard Earth Sciences (GES, <http://disc.sci.gsfc.nasa.gov/>). The monthly rainfall data is available at a spatial resolution of $0.25^\circ \times 0.25^\circ$ (for latitude: 50°S – 50°N ; longitude: 180°W – 180°E) since 1998. We have used monsoon rainfall data for the years 2004 and 2005.

RESULTS AND DISCUSSION

Figure 1(a) shows the distribution of MODIS water vapour over the Indian sub-continent for the years 2004 and 2005. Over the IG plains, water vapour clearly shows a decreasing gradient from east to west in both the years. The Thar Desert shows lowest

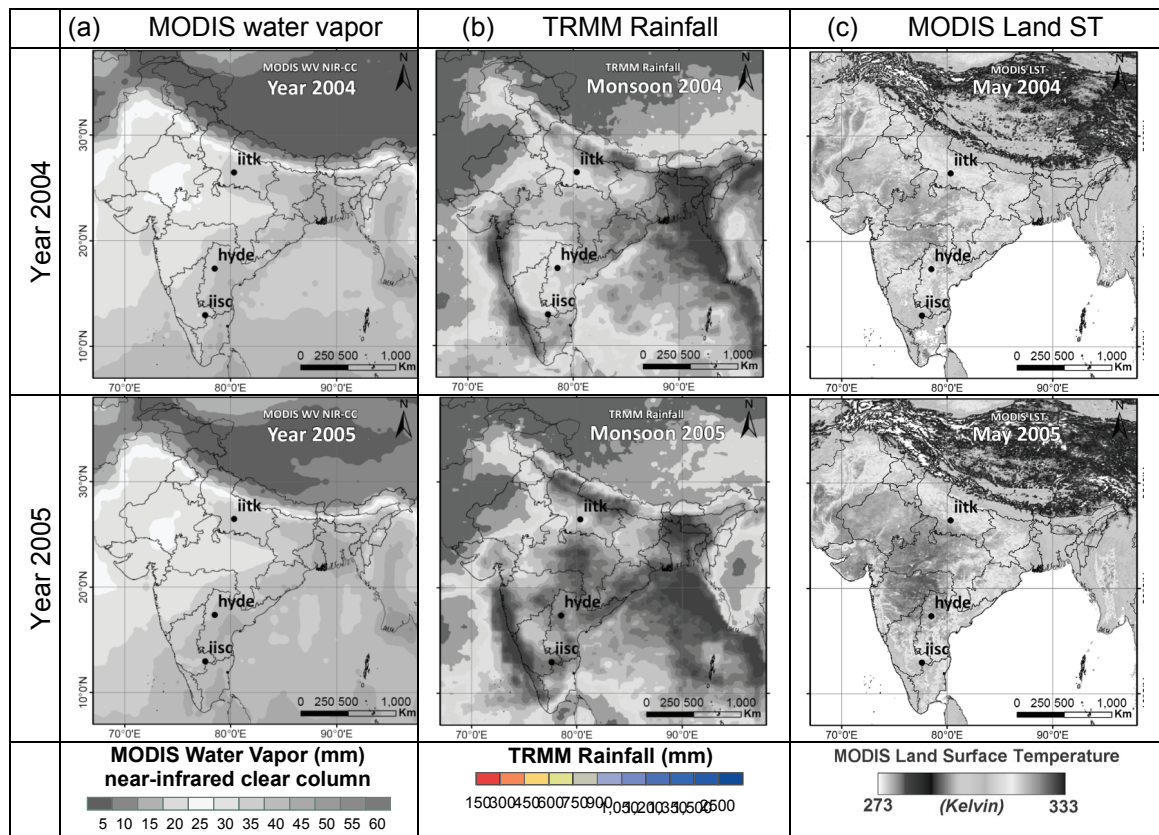


Fig. 1 Comparison of spatial distribution of (a) column MODIS water vapour (near infrared clear column, day time), (b) TRMM monthly monsoon rainfall (mm) and (c) MODIS land surface temperature (May) over the Indian sub-continent during 2004 and 2005.

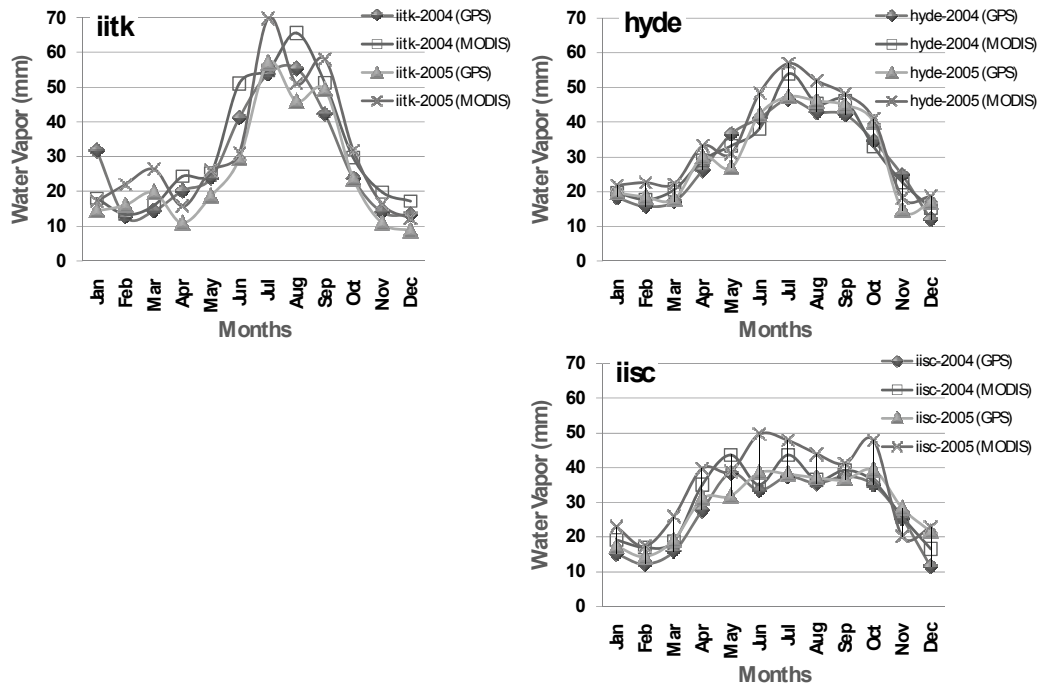


Fig. 2 GPS and MODIS (NIR-CC) derived water vapour (monthly mean) over Kanpur (iitk), Hyderabad (hyde) and Bangalore (iisc) for years 2004 and 2005.

(20–25 mm) (western India) water vapour. The yearly water vapour columns from MODIS for 2004 and 2005 do not show much difference over land (Fig. 1(a)). The distribution of TRMM rainfall (Fig. 1(b)) shows failure of the monsoon during 2004 over the northern plains of India. The year 2005 was observed as one of the warmest years in the last 100 years, which is also seen from MODIS-derived land surface temperature (day time) showing high surface temperatures over the northern plains of India in the summer (May). The monthly and seasonal GPS (over a station) and MODIS (over a larger area) water vapour clearly show intra- and inter-annual features (failure of Indian monsoon, high surface temperature during summer months and formation of fog in the northern plains during winter months).

Comparison of water vapour estimated from GPS and MODIS over the three locations (iitk, hyde and iisc) shows higher estimation of water vapour generally from MODIS (Fig. 2). The correlation coefficient between GPS and MODIS water vapour is found to be more than 0.95. The Kanpur (iitk) station shows high intra-seasonal fluctuations compared to GPS stations in southern India (hyde and iisc). The GPS water vapour is found to be maximum (up to 70 mm over iitk) during the monsoon season and low during the summer season (Fig. 2). During dust storm events (summer season) over the Indo-Gangetic plains, column water vapour is found to be enhanced (Prasad *et al.*, 2007). The column water vapour from GPS shows a large increase with the monsoon onset (usually third week of June or first week of July) and the three phases of the monsoon (onset–break–withdrawal) (Fig. 2, July–October). The water vapour estimates from other satellites such as Special Sensor Microwave/Imager (SSM/I) also show the monsoon onset season (Singh *et al.*, 2004). The iitk and hyde stations show low column water vapour during 2005 compared to 2004 due to high surface temperatures. The summation of monthly fraction (in %) distribution over a

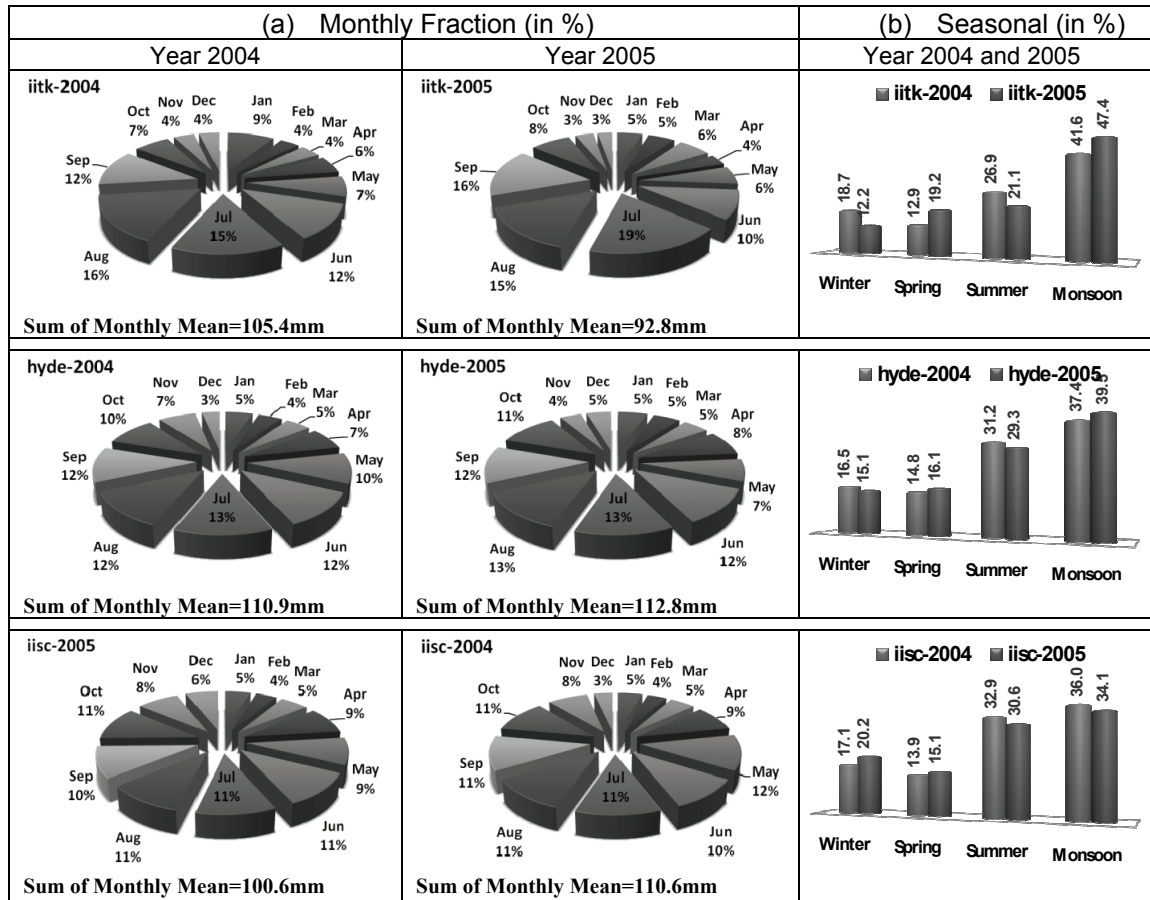


Fig. 3 (a) Monthly fraction of water vapour, and (b) seasonal variability (%) over Kanpur (iitk), Hyderabad (hyde) and Bangalore (iisc) for 2004 and 2005.

year for GPS water vapour shows low column water vapour during year 2005 (iitk = 20%; hyde = 27%) compared to the year 2004 (iitk = 25%; hyde = 29%) during the summer season (Fig. 3(a)). MODIS water vapour also shows the effect of high temperature (during 2005 summer season) where the entire northern plains of India show low water vapour (20–25mm, Fig. 4) compared to the year 2004 (25–35mm). The seasonal fraction (Fig. 3) also shows the effect of high surface temperature on low column water vapour (–5.8% over iitk; Fig. 3). The GPS and MODIS water vapour show a correlation coefficient in the range 0.94–0.99 during summer (April–June 2005), which also indirectly supports the observation of high surface temperature.

The monthly and seasonal column water vapour over iitk and hyde show low value (–5.8% over Kanpur, Fig. 3) during the 2004 monsoon season (compared to 2005), a drought year caused due to failure of the monsoon. GPS and MODIS monthly variations (Fig. 2) show low column water vapour during the 2004 monsoon season compared to 2005. MODIS water vapour (Fig. 4) also clearly shows lower column water vapour especially over the IG plains and central India.

Figure 4 shows low water vapour over the entire IG plains (10–20 mm) and central India up to Hyderabad during the year 2005 (November+December) compared to the year 2004 (20–30 mm). The monthly and seasonal fraction (Fig. 3) show low water vapour over iitk and hyde during November–December 2005; this is expected since,

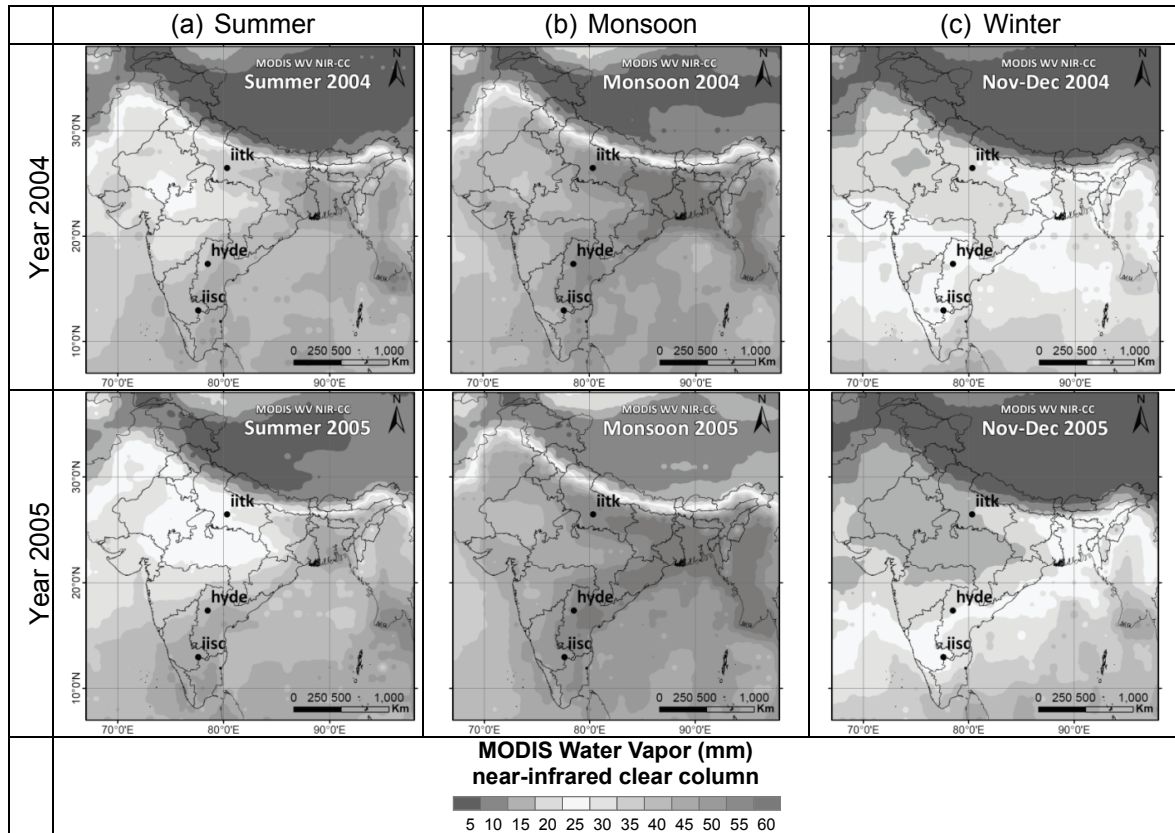


Fig. 4 MODIS water vapour (NIR-CC) distribution (for 2004 and 2005) over Indian sub-continent for: (a) Summer season, (b) Monsoon season, and (c) Winter season.

during the 2005 winter season fog was almost absent over the entire northern plains. In contrast, higher water vapour during the 2004 winter explains dense fog formation over the whole of northern India, especially over the Indo-Gangetic plains. The year 2005 was warmer compared to 2004 along with a large difference in the column water vapour over the northern plains.

Major natural events, such as dust storms, warming during summer, monsoon rainfall, and fog formation during winter, are very dependent on column water vapour. The continuous (hourly average) GPS-derived water vapour supported by satellite observations will be useful in providing detailed information about the change in weather conditions on an hourly basis. The sum of monthly mean water vapour over a year (GPS, Fig. 3) shows yearly variations which may be a resultant effect of climatic and seasonal changes and also the absence of data due to technical problems with GPS.

CONCLUSIONS

The column water vapour estimated from GPS observations is found to be sensitive to surface temperature, drought conditions due to monsoon failure, and the formation of fog during the winter season. These observations from continuously operating GPS water vapour (ground stations) are well corroborated by satellite observations (daily overpass of MODIS) which have a wider spatial coverage as seen over the Indian sub-

continent. The monthly and seasonal fluctuations in water vapour (GPS and MODIS) also clearly show various natural events (such as dust storms) and regional weather and climatic conditions (such as the onset–break–withdrawal of the monsoon). A high correlation coefficient, >0.95 , between the GPS and MODIS water vapour shows the accuracy of measurements. A dense network of ground-based GPS stations together with satellite data such as MODIS will be of great help in improving near real-time weather forecasting and understanding of regional events such as the formation of cloud during the monsoon season and fog during the winter season.

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