551.501.771 : 551.501.86

INTER-COMPARISON OF GPS DERIVED PWV WITH MODIS, NCEP AND RS PWV

1. Estimate of Precipitable Water Vapor (PWV) is very useful in short-term forecasting and numerical weather prediction. It is variable in both space and time, with typical values may range from 10 mm or less over a desert up to 60-70 mm in tropical cyclones. Different methods exist for atmospheric water vapour retrieval from ground-based, airborne and space-borne sensors. Water vapor radiometer and LIDAR (Light Detection and Ranging) are often used for ground based mapping of tropospheric water vapour. In most cases, ground-based sensors have been known to produce high quality data with high vertical and temporal resolutions (England *et al*., 1992; Eichinger, *et al*., 1993, 2000). Their main disadvantage is the limited spatial coverage, which makes the measurements less suitable for regional studies of water vapor transfers. A new technique using Global Positioning System (GPS) data to retrieve atmospheric water vapor (Rocken *et al*., 1993) is found very useful for many atmospheric processes. Atmospheric increases in the concentration of water vapour constitute the single largest positive feedback in models of global climate warming caused by greenhouse gases (Webster, 1994). This study presents a statistical comparative precipitable water vapour (PWV) analysis of the total integrated water vapour or equivalently PWV from Global Positioning System (GPS) Zenith Total Delay (ZTD) data, with Moderate Resolution Imaging Spectroradiometer (MODIS), National Centre for Environment Prediction (NCEP) Reanalysis data and Radiosondes (RS) data.

2. *Data and methodology* - The GPS Zenith Total Delay Data (one day mean) used in this study is obtained from Wadia Institute of Himalayan Geology, Dehradun for the winter months of January and February 2003. The radiosondes data is taken from India Meteorological Department New Delhi for the same period. From NCEP reanalysis data precipitable water vapour in kg/m^2 is available from global site (http://www.cdc.noaa.gov/cdc) at 2.5° Latitude × 2.5° Longitude global grid (90° N - 90° S, 0° E - 357.5° E). The data is extracted and averaged linearly about the station position. The MODIS PWV data is available from global site (http://modis.gsfc.nasa.gov/data). The MODIS atmospheric water-vapour product is an estimate of the total tropospheric column water vapour made from integrated MODIS infrared retrievals of atmospheric moisture profiles in clear scenes. Methodology involves ratios of water vapour absorbing channels centered near 0.905, 0.936 and 0.940 mm with atmospheric window channels at 0.865 and 1.24 mm.

Integrated Water Vapour (IWV) from GPS is retrieved from the ZTD following the concept describe in Bevis *et al*., (1992) and Emardson *et al*., (1998). Firstly, the hydrostatic delay ZHD (m) is calculated as shown below. The Zenith Hydrostatic Delay (ZHD) can be calculated from the local surface pressure.

$$ZHD = (2.2768 + 0.0024)\ P_s / f(\theta, h) \quad (1)$$

Where,

$$f(\theta, h) = 1 - 0.00266 \cos(2\theta) - 0.00028\ h \quad (2)$$

Where, P_s is the surface pressure in hPa and $f(\theta, h)$ is a factor accounting for the variation in gravitational acceleration with latitude and height. The ZHD subtracted from ZTD yields the Zenith Wet Delay (ZWD) and h is the height in km.

$$ZTD = ZHD + ZWD \quad (3)$$

The PWV and IWV are expressed as follows:

$$PWV = KZWD \quad (4)$$

Where, K is a constant defined below :

$$K = \frac{10^6}{(k_3 / T_m + k_2')R_v}$$

Where,

$$k_2' = k_2 - (R_d/R_v)\ k_1$$

The values of k_1, k_2 & k_3 are given above.

R_d = 286.9 J/kg K (Specific gas constant for water vapour)

R_v = 461.51 J/kg K (Specific gas constant for dry air) Integrated mean temperature (T_m) is not known exactly, it can be related to the surface temperature linearly by the empirically derived formula (Bevis *et al*., 1992) :

$$T_m = 70.2 + 0.72\ T_s \quad (5)$$

Using this relation yields an average error in PWV of less than 4% (which is still a conservative error estimate) (Yuan *et al*., 1993).

$$IWV = \rho\ PWV \quad (6)$$

3. *Results and discussions* - Water molecule is the key molecule in radiation transfer and atmosphere physical energy transfer so our aim is to map correctly the zenith wet delay (ZWD) by remote sensing. Remotely sensed data, in case of adequate spatial and temporal coverage, hold the key to a better understanding of the hydrological cycle, atmosphere-biosphere interactions and the Earth's radiation budget as well as to the monitoring of climate change, drought conditions and desertification processes (King *et al.*, 1992). In this paper an effort is done to validate the PWV by different approaches. GPS approach will provide the PWV data in continuous and cost effective manner. This will enhance the NWP activity to better understand the various complex processes of the atmosphere. Inspite of the uncertainties like multi-path and ionospheric noise etc. in retrieval of PWV by GPS zenith total delay it shows fairly good agreement with the MODIS and NCEP data. The inter-comparison of GPS with MODIS, NCEP and RS are shown in Figs. 1 and 2 for New Delhi and Bangalore respectively. The result shown in Table 1 indicates that the root mean square error for New Delhi is less in comparison to Bangalore.

TABLE 1

Root mean square error (RMSE) in mm

Combination	RMSE in mm (New Delhi)	RMSE in mm (Bangalore)
MODIS - GPS	4.5	5.9
NCEP - GPS	5.4	5.0
RS - GPS	4.5	7.6

GPS retrieval is taken without met package for both the stations. This will be one of the major sources of error, because the ZTD results are more sensitive for surface pressure variations. In tropical region the variation of the surface pressure and temperature are more variable so fresh initialization is essential before each outcome. Once it is properly manages then this output will go to numerical weather prediction (NWP) model and this will improve the understanding of micro and meso scale processes. In GPS the value of ZHD is modeled (Saastamoinen, 1972) and calculated from Eqn. 1 and Eqn. 2. The value of ZTD is retrieved from GPS data using GAMIT processing software of MIT, USA. Equations 3 and 4 show how PWV is related ZTD and ZWD. The values of PWV in mm are retrieved from Eqn. 6. Other sources of errors are also included like broadcast ephemeris, receiver and satellite clock biases and receiver noise etc. The atmospheric mean temperature is also modeled by different temperature models. But in this study we have used the mean temperature given in Eqn. 5. The collective comparison is shown graphically in Fig. 1 and Fig. 2 for New Delhi and Bangalore respectively. The NCEP data have poor spatial resolution (2.5 × 2.5) in comparison to MODIS (5.0 km) data. With the help of new algorithms efforts has been

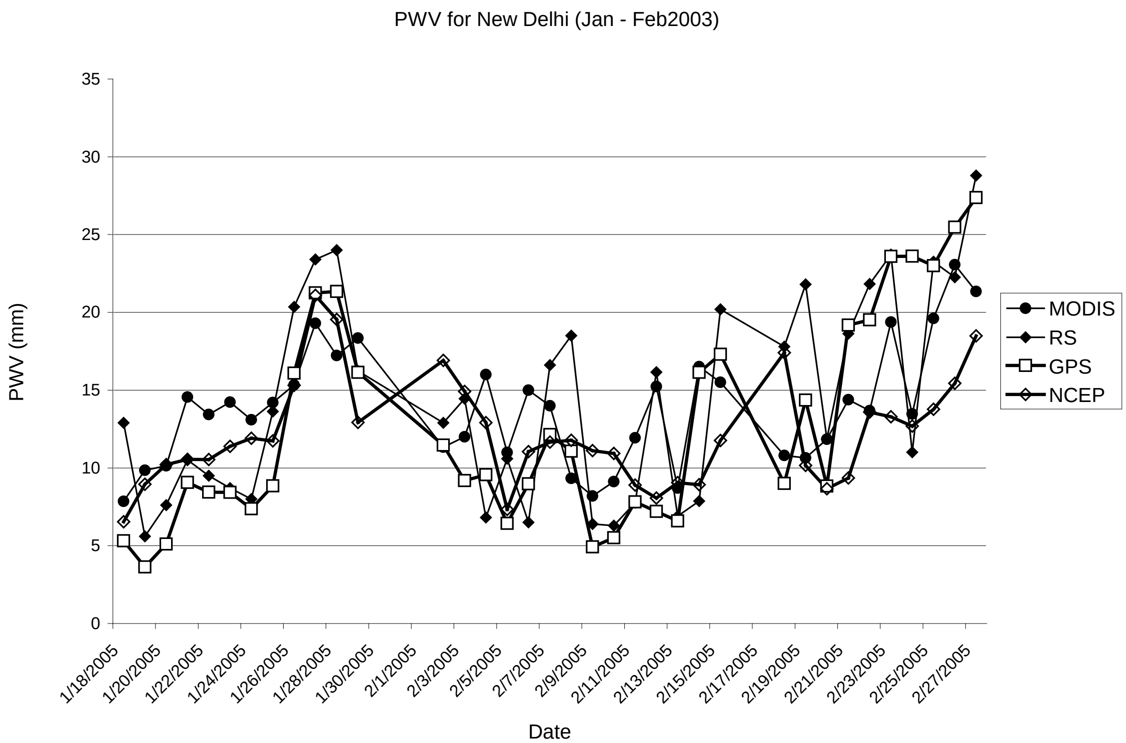

Fig. 1. Precipitable water (mm) comparison MODIS, RS, GPS, GPS and NCEP for New Delhi (Jan – Feb 2003)

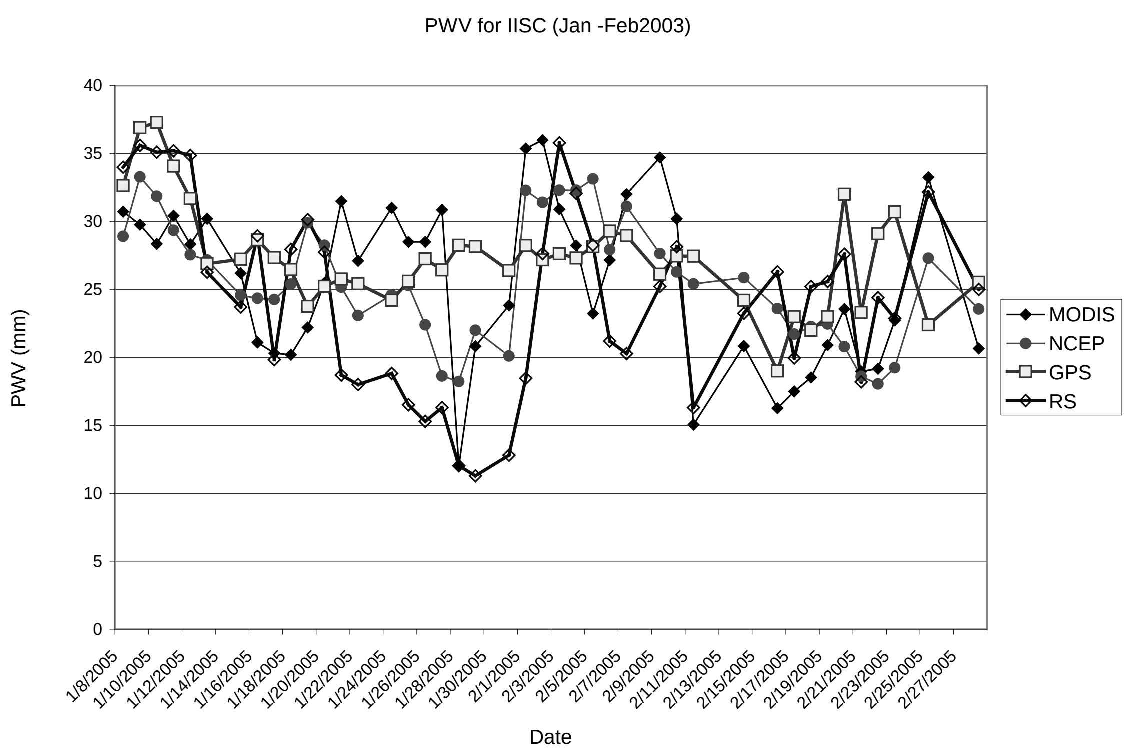

Fig. 2. Precipitable water (mm) comparison MODIS, NCEP, GPS and RS for Bangalore (Jan – Feb 2003)

made to make the products a basis for quantitative scientific publications. Efforts are continuing to make the products (MODIS, NCEP PWV) error free and quality controlled.

4. The following conclusions are drawn from the present study:

(*i*) The root mean square error (RMSE) in the estimation of PWV from GPS for New Delhi and Bangalore stations with MODIS, NCEP and RS combinations are shown in Table 1. The RMSE values for New Delhi are better than Bangalore.

(*ii*) GPS ZTD values are without retrieved without met package for both the stations but the PWV variation with MODIS, NCEP and RS in the case of Bangalore are more this is may be due to more fluctuation in surface pressure and temperature values over the station.

(*iii*) NCEP and MODIS PWV estimation is done by linearly averaged the PWV values around the station position. This is one of the probable sources of high RMSE values.

(*iv*) GPS derived PWV values provide a valuable tool to understand the complexity of the micro and meso scale process in a better way.

5. The authors are grateful to the Director General of meteorology for providing necessary assistance during the course of study. The GPS, ZTD data provided by Dr. P Banerjeee Scientist, Wadia Institute of Himalayan Geology, Dehradun is duly acknowledged.

References

Bevis, M., Businger, S., Herring, T. A., Rocken, C., Anthes, R. A. and Ware, R. H., 1992, "GPS Meteorology : Remote sensing of atmospheric water vapour using the Global Positioning System", *J. Geophys. Res*., **97,** 15787-15801.

Eichinger, W., Cooper, D., Parlange, M. and Katul, G., 1993, "The application of a scanning, water – Raman lidar as a probe of the atmospheric boundary layer", *IEEE Trans. Geosci. Remote Sensing*, **31**, 1, 70-79.

Eichinger, W., Cooper, D., Kao, J., L. Chen, C., Hipps, L. and Prueger, J., 2000, "Estimation of spatially distributed latent heat flux over complex terrain from a Raman lidar", *Agric. For. Meteorol*., **105**, 145-159.

Emardson, T. R., Elgered, G. and Johanson, J., 1988, "Three months of continuous monitoring of atmospheric water vapour with a network of Global Positioning System receivers", *J. Geophys. Res*., **103,** 1807-1820.

England, M. N., Ferrare, R. A., Melfi, S. H., Whiteman, D. N. and Clark, T. A., 1992, "Atmospheric water vapour measurements: Comparison of microwave radiometry and lidar", *J. Geophys. Res.*, **97**, 889-892.

King, M. D., Kaufman, Y. J., Menzel, W. P. and Tanre, D., 1992, "Remote-sensing of cloud, aerosol and water-vapour properties from the moderate-resolution imaging spectrometer (MODIS)", *IEEE Trans. Geosci. Remote Sensing*, **30**, 2-27.

Rocken, C, Ware, R., Van Hove, T., Solheim, F., Alber, C., Johnson, J., Bevis, M. and Businger, S., 1993, " Sensing Atmospheric water vapour with the Global Positioning System", *Geophys. Res. Lett*., **120**, 2631-2638.

Saastamoinen, J., 1972, "Atmospheric correction for the troposphere and stratosphere in radio ranging of satellites," In: Henriksen, S.W., *et al*. (Ed.), Geophysical Monograph Series, vol. 15, American Geophysical Union, 245-251.

Webster, P. J., 1994, "The role of hydrological processes in ocean-atmosphere interactions", *Rev.*36 *Geophys*., **32**, 4, 427-476.

Yuan, L. L., Anthes, R. A. Ware, R. H., Rocken, C., Bonner, W. D., Bevis, M. and Businger, S., "Sensing Climate Change Using the Global Positioning System", *Journal of Geophysical Research*, **98**, D8, 20 August 1993, 14925-14937.

R. K. GIRI*
B. R. LOE
S. K. MUKHERJEE
R. K. SHARMA**
RAJVEER SINGH*
DEVENDRA SINGH

**Mountain Meteorology Centre, Srinagar, India*
India Meteorological Department, New Delhi, India
*** N. A. S. Degree College, Meerut (U. P.), India*
(*26 December 2005, Modified 4 September 2006*)