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Validation of GPS-based estimates of integrated water vapour for the Australian region and identification of diurnal variability

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We compare estimates of integrated water vapour derived from ground-based Global Positioning System (GPS) and nearby surface meteorological data, with estimates derived from radiosonde soundings and from two global numerical weather prediction systems over the Australian Region for the year 2000. The relative accuracies of GPS-based estimates for sites with co-located radiosondes are similar to those reported in previous studies for other regions of the world, with the exception of Antarctica. For eight GPS sites with nearby radiosonde launch sites, an average GPS-integrated water vapour estimation standard deviation error of 8.8 per cent over the year 2000 was obtained, relative to that of radiosonde estimates. Respective percentage errors of 10.7 and 18.0 obtained for integrated water vapour derived from analyses and six-hour forecasts of the Australian Bureau of Meteorology's operational global numerical weather prediction system for 2000, indicate the potential of GPS estimates, when comprehensively available for assimilation, to significantly reduce such errors. Marked precipitable water diurnal variations in the time series of GPS-based data were also detected. The variations, averaged over one year, were found to be very similar to variations in GPS-derived zenith wet delay at all GPS sites. The potential of using GPS estimates of precipitable water for monitoring the performance of numerical weather prediction system moisture variables is indicated.

Introduction

Accurate representation of the spatial and temporal distribution of water vapour in the atmosphere represents a significant challenge in current meteorological practice. The quality of quantitative precipitation forecasting and of model representation of hydrologic processes is clearly dependent on accurate initialisation of the atmospheric moisture distribution.

Atmospheric water vapour is often quantified in kg/m^2 as the vertically integrated mass of water vapour per unit area, or in mm as the height of an

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equivalent column of liquid water, termed precipitable water (PW). Numerically 1 kg/m^2 of water vapour is equivalent to 1 mm PW. We also use the term 'integrated water vapour' (IWV) when referring to various estimates or measurements of PW, as is common in the literature.

Traditional PW sensors include ground and satellite-based water vapour radiometers (WVRs), radiosondes, ground-based humidity sensors and sensors on research aircraft. More recently, the Global Positioning System (GPS), whilst designed as a military navigation and positioning aid and now comprising some 29 satellites, has evolved into an IWV sensor accessible by civilians. Ground-based GPS receivers track the satellites and record data, which may be processed to provide high temporal frequency estimates, as often as every 15 minutes, of IWV in all weather at a spatial resolution that depends solely on the number of receivers deployed.

The capability of GPS to deliver continuous, high temporal frequency measurements of IWV is anticipated to be very useful for current numerical weather prediction (NWP) systems, particularly in improving quantitative precipitation forecasts. Bevis et al. (1992) first proposed the use of ground-based GPS IWV (GPS_IWV) estimates for meteorology. Since then numerous studies for different regions of the world have been conducted to assess its quality. A GPS_IWV estimation accuracy of 1 to 2 mm under ideal conditions has been well documented (e.g. Bevis et al. 1994; Duan et al. 1996; Tregoning et al. 1998), including near real-time demonstrations (e.g. Dick et al. 2001) and applications (Gutman et al. 2004). Such IWV accuracy is desired by meteorologists for use in assimilation and NWP systems (Baker et al. 2001). Consequently the availability of high frequency measurements of GPS_IWV has attracted considerable interest in establishing their usefulness.

Assimilation and prediction systems of the Australian Bureau of Meteorology (ABM) do not yet make use of GPS_IWV. Before embarking on the development of any operational system for the incorporation of GPS_IWV in Australian NWP, it was considered essential to undertake a validation study of the accuracy with which GPS_IWV may be estimated from ground-based GPS receivers across Australia. The only previous work on GPS_IWV estimation over the Australian region, using somewhat limited datasets, was undertaken by Tregoning et al. (1998) and later Feng et al. (2003). Tregoning et al. (1998) compared GPS, WVR and radiosonde estimates of IWV at Cape Grim Tasmania through November and December 1995, reporting differences between the instrument measurements of just less than 1.5 mm. Feng et al. (2003) assessed GPS_IWV relative to co-located radiosonde estimates for five sites across the Australian region from July to September 2000, finding mean differences between GPS and radiosonde estimates of 0.66 mm, root mean square (rms) errors of 1.92 mm and standard deviations of 1.80 mm for 500 comparisons after discarding outliers.

To assess the accuracy of GPS_IWV estimation, we chose to use all readily available GPS data from seventeen sites across continental Australia, island territories and Antarctica for the whole of 2000, thus covering four seasons and a wide range of climates. Our initial studies focused on validating GPS_IWV estimates against data from other meteorological sensors and products from NWP systems in order to examine the feasibility of using GPS data in the ABM assimilation and prediction systems. Extensive comparisons of IWV estimated from GPS, radiosondes, the ABM Global Assimilation and Spectral Prediction (GASP) and European Centre for Medium-range Weather Forecasts (ECMWF) NWP systems were performed for this period. Such comparisons can support a derivation of quality indicators for GPS_IWV estimates needed for effective assimilation of this data into NWP systems. Furthermore, the comparisons also provide some insight into the quality of moisture analysis by both GASP and ECMWF systems and of GASP forecasts. Finally, we considered whether diurnal variability of IWV could be detected across Australia using GPS since this has not previously been reported and has the potential for improving the validation of NWP system moisture accuracy.

In what follows, relevant background theory for the retrieval of IWV from GPS is provided. The details of the datasets and specific procedures implemented when estimating IWV across the Australian region using GPS, radiosondes and NWP systems are described. An intercomparison is made of IWV estimates obtained using these three methods and results of IWV diurnal variability obtained from GPS are presented. Some factors affecting the accuracy of GPS IWV estimates are discussed, with conclusions, outlooks and suggestions for further work.

Basic theory

The Global Positioning System currently comprises 29 navigation satellites at an altitude of about 20,200 km, grouped in six planes evenly distributed around the equator, having orbital periods of just under 12 hours. For precise navigation a ground-based GPS receiver tracks and records carrier phase measurements simultaneously from as many as ten satellites, accumulates the data over time and estimates parameters such as receiver coordinates. In order to estimate coordinates to the greatest accuracy, it is necessary to mitigate all sources of error that affect the carrier phase measurements. A major source of error is the atmosphere affecting the speed of signal propagation from satellite to ground-based receiver. However, whilst the amount of atmospheric propagation delay is considered noise for applications such as positioning, since its value is dependent on the atmospheric composition, it can be converted to a signal for use in applications such as meteorology.

In GPS work, the atmosphere is considered to comprise the 'neutral atmosphere' to a height of about 50 km above the earth's surface and the ionosphere from about 50 to 1000 km above the surface. The ionospheric refraction may be almost completely eliminated by comparing the effect of this refraction at two frequencies that are dispersed at a known rate. The delay due to the neutral atmosphere, which does not disperse the different GPS radio frequencies, must be modelled or estimated and cannot be easily eliminated. The neutral atmosphere is conventionally just termed the 'troposphere' in GPS work, since about 75 per cent of the delay is caused by the lowest 10 km of the atmosphere, which corresponds closely to the meteorological troposphere. Using a mapping function, the tropospheric delay experienced along each receiver-to-satellite path may be mapped to the zenith and a single zenith total delay (ZTD) parameter estimated per receiver site. In practice, ZTD is estimated as a constant parameter per receiver site over intervals of around fifteen minutes to one hour. The ZTD estimated in scientific geodetic-GPS software represents a least-squares best-fit mean of all zenith-mapped signal slant-path delays from receiver to each visible satellite over the time interval considered. This procedure is adopted regardless of atmospheric conditions.

The ZTD that is obtained from a GPS software package can be considered to comprise a zenith hydrostatic delay (ZHD) and a zenith wet delay (ZWD). ZHD is dependent on surface pressure, site latitude and height, and may be computed, following Elgered et al. (1991), as

$$ZHD(P_0,\phi,h) = \frac{2.2779\ 10^{-5}\ P_0}{1 - 2.66\ 10^{-3}\cos(2\phi) - 2.8\ 10^{-7}h} \quad \ldots 1$$

where
P_0 is the total pressure at the GPS antenna height (Pa),
ϕ is the site latitude (degrees),
h is the height of the site above the (international) ellipsoid (m),
the constant 2.2779 10^{-5} is in m/Pa,
the constant 2.8 10^{-7} is in m^{-1},
and ZHD is in metres.

ZHD values are typically around 2.3 m, but can be estimated accurately using Eqn 1 if pressure P_0 measurements are available. For example, pressure data accurate to 0.3 hPa yields a ZHD accuracy of about 1 mm.

ZWD is largely dependent on the quantity of atmospheric water vapour and can vary from around 0 mm in polar regions to over 400 mm in the tropics. It may be simply obtained by subtraction

$$ZWD = ZTD - ZHD(P_0,\phi,h) \quad \ldots 2$$

Any errors in the modelled hydrostatic delay will propagate to the ZWD. At GPS sites co-located with meteorological surface stations, the error in the pressure observed by a barometer should not exceed 0.3 hPa and therefore the hydrostatic delay there can be computed to within 1 mm accuracy. At GPS sites without co-located barometers, the pressure must be estimated from the nearest barometer, so larger errors in ZWD will be expected there. Alternatively, NWP system surface pressure can be used, where errors would depend on the NWP system interpolated output (analysis or forecast) accuracy.

ZWD may be converted to IWV via a dimensionless conversion factor Q (Askne and Nordius 1987) that is dependent on the mean temperature of the atmosphere for the site in question and is given as

$$IWV = ZWD/Q \quad \ldots 3$$

and

$$Q = 10^{-6}\rho R_v\,(k_3/T_m + k_2') \quad \ldots 4$$

where
ρ is the density of liquid water (1000 kg/m^3),
R_v is the specific gas constant of water vapour (461.524 $Jkg^{-1}K^{-1}$),
k_3 and k_2' are atmospheric refractivity constants (0.037x10^5 K^2/Pa and 0.22 K/Pa respectively) and
T_m (K) is the moisture-weighted mean temperature of the troposphere (Davis et al. 1985) defined as

$$T_m = \frac{\int (e/T)dh}{\int (e/T^2)dh} \quad \ldots 5$$

where
e is partial water vapour pressure (Pa),
T is temperature (K) as a function of height h.

The integrations are from the surface, actually the GPS antenna height, to the top of the troposphere. However, in practice T_m is often approximated by the Bevis regression formula (Bevis et al. 1992) based on radiosonde profiles from continental USA:

$$T_m = 70.2 + 0.72T_s \quad \ldots 6$$

where T_s is the temperature (K) at GPS antenna elevation rather than at the surface.

The main uncertainty when converting ZWD to IWV is the estimation of T_m. It was considered beyond the scope of this initial validation study to derive new regressions at all radiosonde sites. For comparison local regressions were derived at a few sites co-located with GPS ground stations. Another source of error is ignoring the small contribution of liquid water in the conversion from ZWD to IWV (Eqn 3). For example, Elgered (1993) estimated an upper bound of 7.5 mm for the delay due to liquid water. Typical values for Q are approximately six, so 6 mm of ZWD is equivalent to about 1 mm of IWV.

Dataset description

All accessible GPS data from dual frequency receivers across the Australian region and territories were collated for the entire year 2000. This gave the largest dataset with which to validate GPS_IWV. The seventeen GPS sites used are shown in Fig. 1. These sites predominantly form the Australian Regional GPS Network maintained by Geoscience Australia, whose data are also made available through the International Global Navigation Satellite Systems (GNSS) Service (IGS). All receivers were equipped with choke ring antennas and recorded carrier-phase GPS measurements every 30 seconds throughout 2000, except for times of occasional communication failures when small quantities of data were lost.

To convert ZTD to IWV, three-hourly surface pressure and temperature recordings from the weather station nearest to each GPS receiver were obtained from the ABM's Australian Data Archive for Meteorology (ADAM). Similarly, daily radiosonde observations from the nearest Australian Upper Air Network site were obtained. All data corresponding to the original signals from sensors were retrieved and used. Atmospheric soundings were obtained by Vaisala RS80-A radiosondes manufactured between September 1988 and May 2000. These radiosondes suffer from a dry bias in relative humidity, which may be estimated by using a formula proposed by Wang et al. (2002). Two NWP systems were selected for computing IWV, namely ABM's GASP, since it is the system developed by ABM and the highly sophisticated ECMWF system. The 2000 operational GASP system is largely as described in Seaman et al. (1995) and in Bourke et al. (1995). Relative to the system described in these references the overall resolution in 2000 had been upgraded to T239/L29, with the prediction model differing primarily with respect to its use of semi-Lagrangian time-stepping and improved convective parametrisation. The ECMWF global assimilation and prediction system is as described by Simmons and Hollingsworth (2002).

Fig.1 GPS sites with nearby radiosonde sites used in this study.

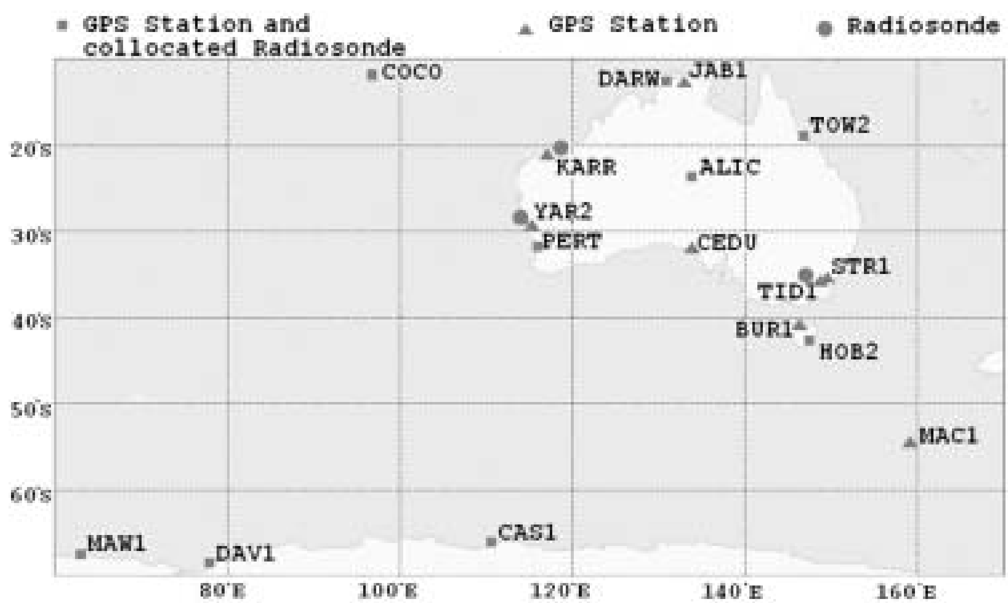


Table 1. GPS site list showing geographical coordinates, horizontal and vertical separation from nearest surface meteorological site and radiosonde launch site. Latitudes and longitudes are positive north of the equator and in the eastern hemisphere. The '#' symbol denotes GPS sites without a nearby radiosonde site. The number of GPS solutions and ZTD estimates for the year 2000 are shown in the last two columns.

Site	*GPS ID*	*Lat*	*Long*	*Height*	*GPS / Surf. Station Sep.*	*GPS / Radiosonde Sep.*			*No. Sol Days*	*No. ZTD Est.*
		(deg)	*(deg)*	*(m above msl)*	*Horiz. (km)*	*Height (m) Surf. - GPS*	*Horiz (km)*	*Height (m) RS - GPS*		
Cocos Island	COCO	-12.2	96.8	5	0.1	-1	0.1	-2	360	8640
Jabiru #	JAB1	-12.7	132.9	28	0.1	0	-	-	308	7392
Darwin	DARW	-12.8	131.1	75	26.0	30	53.2	-45	324	7776
Townsville	TOW2	-19.3	147.1	31	30.2	-21	30.2	-23	362	8688
Karratha	KARR	-21.0	117.1	117	23.2	-104	172.2	-111	340	8160
Alice Springs	ALIC	-23.7	133.9	588	13.8	-41	13.8	-42	359	8616
Yaragadee	YAR2	-29.0	115.3	268	67.6	4	68.7	-235	293	7032
Perth	PERT	-31.8	115.9	46	13.0	-20	16.4	-30	309	7416
Ceduna #	CEDU	-31.9	133.8	154	30.9	-138	-	-	359	8616
Mt Stromlo	STR1	-35.3	149.0	781	17.3	-201	141.3	-569	354	8496
Tidbinbilla	TID1	-35.4	149.0	647	10.6	-59	140.0	-435	276	6624
Burnie #	BUR1	-41.1	145.9	5	16.6	7	-	-	261	6264
Hobart	HOB2	-42.8	147.4	45	6.2	-18	6.2	-41	356	8544
Macquarie I.	MAC1	-54.5	158.9	14	1.1	-6	1.1	-8	342	8208
Casey	CAS1	-66.3	110.5	39	0.9	3	0.9	1	362	8688
Mawson	MAW1	-67.6	62.9	30	0.4	-14	0.4	-20	354	8496
Davis	DAV1	-68.6	78.0	27	0.0	-5	0.0	-11	314	7536

Table 1 lists the geographical coordinates of each GPS site, as well as the horizontal and vertical separations between these sites and the corresponding surface meteorological stations and radiosonde sites that were used to convert GPS estimated ZTD to IWV and for the comparisons between GPS IWV and radiosonde IWV. It can be seen that the horizontal separations vary from about 100 m at GPS sites DAV1, COCO, MAW1, CAS1 and MAC1 to 170 km at KARR. Vertical separations vary from 1 m at CAS1 to 569 m at STR1. These variations must be considered when interpreting any IWV comparisons from the different sensors. The GPS sites JAB1, BUR1 and CEDU were considered too distant from any radiosonde site for comparisons to be meaningful.

Data availability per site is summarised in the last two columns of Table 1, which show the number of daily GPS network solutions for each GPS site, and the number of ZTD estimates available per site during 2000. Significant raw GPS data loss occurred for BUR1 (June to mid-August), JAB1 (January and February), TID1 (January to March) and YAR2 (January and February). Problems with GPS data preprocessing arose for DAV1, causing its exclusion for nearly 50 days, whilst four days of data for the entire network, namely days-of-year 57, 58, 246 and 247 were not used due to orbit modelling problems. For the remaining sites, the number of daily solutions is usually less than 362 due to missing or incomplete raw GPS data for a particular day, usually due to communication failures.

Data processing and computation of IWV estimates

The specific methods used to compute IWV above the GPS antenna from GPS Receiver Independent Exchange (RINEX) format data, radiosonde data and NWP systems will be described so that meaningful comparisons between the three techniques may be carried out.

Computation of ZTD from GPS data

The GPS data from the seventeen sites were processed as a single network using the Bernese geodetic GPS software version 4.2 (Hugentobler et al. 2001). This software compares the simultaneous GPS observations of the same satellites from multiple ground sites to eliminate common errors due to satellite orbits and poor synchronisation between satellite and ground site clocks. The GPS baselines were formed to maximise the number of double difference observations, with the satellite positions tightly constrained to those from the final (latency about 13 days) IGS precise ephemeris, which has a positional quality of about 5 cm and is sufficient for enabling an IWV accuracy of 1 mm (Ge et al. 2000). The final IGS earth rotation parameter estimates were also used. The effect of ionospheric refraction was minimised by linearly combining dual frequency GPS data. Earth-body and ocean tide-loading effects were corrected by using the IERS Conventions (McCarthy 1996) and the GOT00.2 ocean tide model (Ray 1999) respectively. Receiver antenna phase centre variations were corrected using the IGS phase centre models (ftp://igscb.jpl.nasa.gov/pub/station/general/igs_01.pcv).

The continuous data were processed in discrete 24-hour solutions using a 180 second data sampling interval and a minimum elevation cut-off of 15°. Receiver-to-satellite elevation-angle data weighting was used, with estimates of all ambiguities left as floating point, i.e. not integer-fixed. This was to ensure a consistent strategy and solution comparison across the entire network. GPS site marker coordinates were constrained to within 1 cm of the ITRF2000 estimates (Boucher et al. 2004) for each daily processing session to improve the decorrelation between the estimated station coordinates and tropospheric delays. A one-centimetre constraint, instead of very tight 'fixing', was applied to ensure the solutions were not biased by unexplained seasonal coordinate time series effects (Dong et al. 2002) or any unaccounted errors. The ZTD was computed by estimating a zenith correction to the Saastamoinen (1972) model delay estimate per site per hour, using the Niell (1996) mapping function. Relative constraints of 2 mm were applied between adjacent tropospheric estimates and the discrete 24-hour solutions from three consecutive days were combined at the post-processed normal equation level (Brockmann 1996) to provide the final ZTD estimates for each 'middle' day. This follows the procedure of Vedel et al. (2004) to overcome any jumps in the ZTD time series at processing session boundaries.

Computation of ZHD, ZWD and Q above the GPS antenna

To compute the ZHD above the GPS antenna using Eqn 1, the pressure data collected at the nearest surface weather station were mapped from the barometer height above sea level to that of the GPS antenna according to the WMO (1968) formula, with horizontal pressure variations ignored. The computed ZHDs at each station were available at three-hourly intervals that correspond to the timing of pressure observations at the weather stations, while one-hourly ZTD estimates were computed using the GPS data. Therefore the three-hourly ZHD estimates were interpolated to the epoch of the ZTD estimate (using eight-knot cubic splines). To test the errors associated with this approach, pressure data collected every 60 seconds from a Paroscientific Met3 sensor, co-located with the TOW2 GPS antenna, were used as a reference and compared with the hourly estimates of pressure throughout 2000. The mean and rms of the differences were 0.002 hPa and 0.17 hPa respectively, suggesting that the interpolation caused errors of about 1 mm in ZHD. Similarly, when extrapolating the nearest surface station temperature T_s to the GPS antenna level, only the height dependence was considered using a fixed lapse rate of 0.0065 K/m. The conversion factor Q was computed at three-hourly intervals with T_s at GPS antenna level in Eqn 6, then interpolated to the ZWD epochs using eight-knot cubic splines. This gave GPS_IWV estimates above each GPS antenna at hourly intervals for the whole of 2000.

Computation of IWV from radiosonde soundings

Radiosonde IWV (RS_IWV) estimates may be obtained using all available complete soundings from radiosonde pressure, temperature, dew-point temperature and height recorded along the ascending balloon's path. For IWV comparisons of estimates derived from radiosondes and GPS, the RS_IWV estimates can be corrected for the difference in height between the radiosonde surface data and the GPS antenna.

For the column bounded by the GPS antenna height Zb (at pressure Pb) and the top radiosonde recording level ZT (at pressure PT), IWV in kg/m^2 is given by

$$IWV = \int_{Zb}^{ZT} \rho_v dh = -\frac{1}{g} \int_{Pb}^{PT} q dP \qquad ...7$$

where

ρ_v is the density of water vapour (kg/m^3) in the column integrated from Zb to ZT,

dh is the height difference (m) between layers,

q is the specific humidity (mass mixing ratio, kg/kg) computed from discrete radiosonde reports,

dP is the pressure difference (Pa) between layers,

g is the acceleration due to gravity (m/s^2).

Given radiosonde measurements of dew-point temperature T_d (K) and pressure P (Pa), the partial water vapour pressure e (Pa) for temperatures warmer than –50.01°C, was computed using a simplified saturation vapour equation (Gueymard 1993):

$$e = \exp\left\{26.9348692 - \left(\frac{4914.0396 + 109218.53/T_d}{T_d}\right) - 0.00390151 56 T_d\right\} \quad ...8$$

and the specific humidity q using

$$q = \frac{0.62198e/(P-e)}{1 + 0.62198e/(P-e)} \quad ...9$$

RS_IWV was computed above the GPS antenna using the radiosonde soundings from the nearest launch site as input to Eqns 7, 8 and 9, with horizontal water vapour variations ignored.

Computation of IWV from GASP and ECMWF NWP systems

The objective analysis of mixing ratio from GASP and relative humidity from the ECMWF global NWP systems obtained from the ABM archives at the listed pressure levels were first horizontally interpolated to GPS locations, then converted to specific humidity and integrated above the GPS locations to obtain IWV (Eqn 10).

$$IWV = \frac{1}{g}\sum_{j=1}^{n-1} (q((P_j+P_{j+1})/2)+(q_j+q_{j+1})/2)\,(P_j-P_{j+1})/2 \quad ...10$$

where

P_1 is the pressure at the GPS antenna height and

P_j for each j=2, ... n are sequential NWP level pressures. The values of q_1 at P_1 and of q were calculated assuming q varies as logarithm of pressure between analysis levels, and whenever P_1 was greater than 1000 hPa q_1 was assumed equal to specific humidity at the first model level (1000 hPa).

GASP:
10 levels (1000, 850, 700, 600, 500, 400, 300, 200, 150, 100) hPa
1.5 x 1.5 degrees;

ECMWF:
11 levels (1000, 925, 850, 700, 600, 500, 400, 300, 200, 150, 100) hPa
2.5 x 2.5 degrees.

Comparisons of IWV estimates from GPS, radiosondes, GASP and ECMWF NWP systems

Intercomparisons of GPS_IWV, RS_IWV, IWV derived from the GASP (GASP_IWV) and ECMWF (ECMWF_IWV) NWP system analyses, and six-hour forecasts for GASP (GASPfg_IWV) were carried out. The objective was to validate GPS retrieval procedures under different climatic conditions of the southern hemisphere, and to gauge the accuracies of the year 2000 operational analyses (and six-hour first-guess forecasts) representation of IWV relative to operational radiosonde data and independent GPS estimates.

In GASP, the 3D moisture field is determined by the GASP six-hour first guess and by moisture and moisture-sensitive observations. Enhancing observations with GPS_IWV data should theoretically contribute to the reduction in analysis error. To be useful for data assimilation, the new GPS_IWV data should have well-understood and easy-to-describe error characteristics such as known random error, minimum gross errors, small or well-known correlations and be bias free. The comparisons of GASPfg_IWV and GPS_IWV relative to radiosondes provide an indication of the possible benefit of assimilating GPS_IWV data. As will be shown in the following, its relative accuracy is significantly greater at most GPS sites than that of GASPfg_IWV prior to assimilation. GPS_IWV can thus contribute new information when assimilated and is expected to contribute significantly to the reduction of the remaining unexplained variance in analysed GASP moisture field. Due to the differences in the resolution of the archived output of the two NWP systems, which affect the accuracies of the retrieved NWP IWV and thus slightly obscure comparison results, direct intercomparison of GASP and ECMWF derived IWV is not a specific focus of this study.

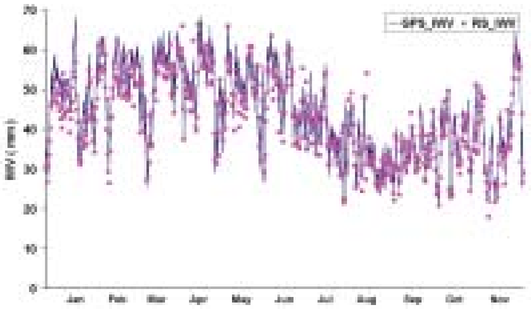
Comparison of IWV from GPS and radiosondes

Estimates of GPS_IWV and RS_IWV above the GPS antenna were compared for the year 2000 for fourteen GPS sites that are co-located with or near radiosonde sites. Figure 2 provides graphical comparisons of GPS_IWV and RS_IWV for COCO, DARW, ALIC and MAW1 for twelve months. The RS_IWV is shown depending on the availability of the radiosonde reports, twice daily for COCO, DARW and MAW1, or once daily for ALIC.

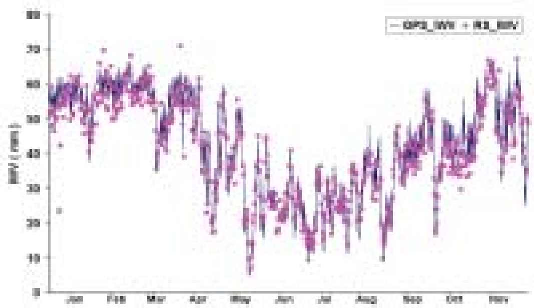
A strong correlation between the GPS_IWV and RS_IWV is clearly seen in Fig. 2, and the comparison statistics for the fourteen selected sites are listed in Table 2. These are also summarised graphically in Fig. 3 together with the average GPS_IWV for each site. The largest standard deviations occur at sites where atmospheric moisture is the highest or where the distance between the GPS site and the radiosonde or surface station is large. For example, KARR is 172.2 km from the nearest radiosonde site at Port Hedland and TID1 and STR1 are both

Fig. 2 **Comparison of GPS_IWV and RS_IWV for (a) COCO, (b) DARW, (c) ALIC and (d) MAW1. Radiosonde estimates were available twice daily, except at ALIC where they were only available once per day.**

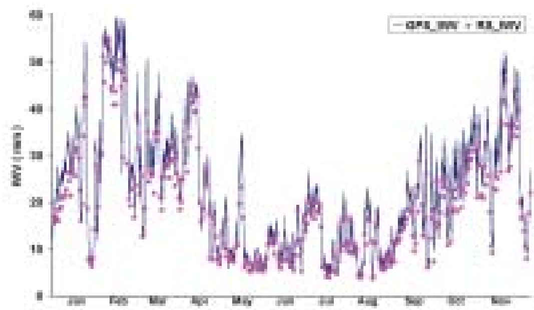
(a) COCO



(b) DARW



(c) ALIC



(d) MAW1

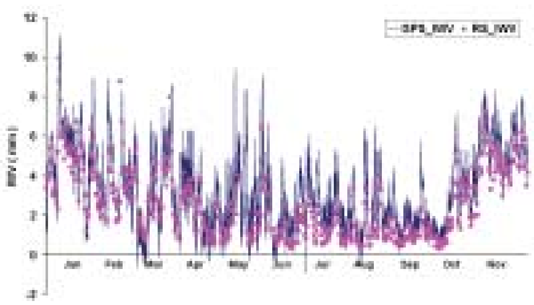
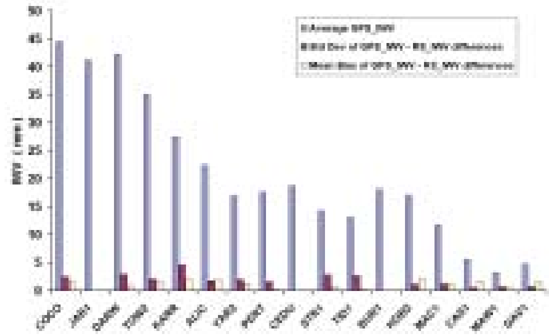


Fig. 3 **Year 2000 average GPS_IWV at 17 GPS sites and comparison statistics of GPS_IWV minus RS_IWV.**



approximately 140 km from the nearest radiosonde site at Wagga Wagga. These findings match those of Liou et al. (2001), who suggest that the magnitude of the standard deviation of the difference between GPS_IWV and WVR IWV estimates relates to the magnitude of IWV. They report an average value of 2.2 mm for Taipei and Guam located near the tropics between 18 and 24 March 1998. In this study, the standard deviations of GPS_IWV and RS_IWV differences for COCO, DARW and TOW2 are of similar magnitude. The standard deviation of 1.1 mm for HOB2 is similar to the two-month average from November to December 1995 reported by Tregoning et al. (1998) for Cape Grim, Tasmania of 1.5 mm between GPS_IWV and RS_IWV and 1.3 mm between GPS_IWV and WVR_IWV. Furthermore, Feng et al. (2003) report a GPS_IWV minus RS_IWV standard deviation of 1.8 mm and a mean difference of 0.66 mm for five GPS sites for July to September 2000, with T_m derived from radiosondes. However, July to September is a period of reduced tropospheric water vapour at all their five GPS sites when compared to the yearly average. For ALIC, DARW and TOW2 it is only 54, 60 and 62 per cent respectively of the yearly amount. When scaled, for a given site, by the amount of water vapour, the standard deviations reported by Feng et al. (2003) and those obtained in this study (Table 2) are very similar. The standard deviation is typically less at higher latitudes since it is a function of the amount of IWV. It is apparent from Table 2 and Fig. 3 that the GPS estimates all show a positive bias relative to radiosondes, varying from 0.5 mm at DARW to about 2.2 mm in Hobart.

Table 2. Comparison of GPS_IWV with RS_IWV for the year 2000. Outliers omitted at the 3.5 standard deviation level. N is the number of comparison time points. IWV values are expressed in mm. The last column shows the correlation coefficients between GPS_IWV and RS_IWV.

Site ID	*N*	*Ave RS_ IWV*	*Ave GPS_ IWV*	*rms*	*Std dev*	*Mean bias*	*Std dev /Ave RS _IWV %*	*Corr*
COCO	700	42.9	44.4	2.9	2.5	1.5	5.8	0.97
DARW	645	41.0	41.9	3.0	2.9	0.9	7.0	0.98
TOW2	357	32.3	34.0	2.7	2.1	1.7	6.5	0.99
KARR	737	26.6	28.6	5.0	4.6	2.1	17.3	0.95
ALIC	350	19.4	21.5	2.7	1.8	2.0	9.3	0.99
YAR2	368	14.9	16.2	2.4	2.0	1.3	13.4	0.98
PERT	607	17.2	17.4	1.6	1.6	0.2	9.3	0.98
STR1	414	12.8	13.5	2.9	2.8	0.7	22.0	0.93
TID1	330	12.4	12.6	2.7	2.7	0.2	21.8	0.92
HOB2	709	14.4	16.7	2.5	1.1	2.2	7.6	0.98
MAC1	662	10.4	11.5	1.7	1.2	1.1	11.5	0.96
CAS1	580	3.3	5.1	1.9	0.6	1.8	18.2	0.91
MAW1	660	2.6	3.0	0.9	0.7	0.5	26.9	0.92
DAV1	589	2.9	4.5	1.7	0.7	1.6	24.1	0.89

Comparison of IWV from radiosondes with GASP and ECMWF analyses

Table 3 provides a summary of the accuracy of integrated moisture in the two NWP system analyses for the entire year 2000 relative to radiosondes. It can be seen that both GASP and ECMWF analyses have predominantly moist biases relative to radiosonde estimates. Excluding the Antarctic sites, the average biases are 1.09 mm for GASP and 1.01 mm for ECMWF. This means that both GASP and ECMWF mixing ratio analyses yield IWV values that are systematically larger than respective radiosonde observations. We link these relative underestimates in RS_IWV to dry biases in Vaisala RS80-A humidity measurements as they have more effect on estimates of RS_IWV than on NWP analyses of IWV. The latter are corrected in part by model physics, but also have contributions from other measurements of moisture. The corresponding average standard deviations of IWV estimates relative to radiosondes for these non-Antarctic stations are 2.66 mm for GASP and 2.59 mm for ECMWF.

Comparison of IWV from GPS with GASP and ECMWF analyses

A comparison of GPS_IWV estimates with GASP_IWV and ECMWF_IWV from operational analyses is shown in Table 4 for all seventeen GPS sites. Results indicate that GPS_IWV estimates are, in most cases, slightly larger than respective GASP_IWV and ECMWF_IWV and for Antarctic stations substantially larger. We have just seen that the GASP_IWV and ECMWF_IWV are also biased positively with respect to radiosondes (Table 3). That is the GPS_IWV and numerical analyses are somewhat surprisingly (as both NWP systems assimilate radiosonde data) in closer agreement than GPS_IWV and RS_IWV. Comparison with NWP system analyses also allows GPS_IWV verification and vice versa, which is useful at locations such as BUR1, CEDU and JAB1 where radiosonde reports are not available to the assimilation systems. Standard deviations for these sites are somewhat larger as seen in Table 4.

The comparison performed separately for 0000 UTC and 1200 UTC as in Table 5, when considered in conjunction with the composite results of Table 4, provides an indication of the effect of radiosonde data. ALIC and TOW2 were selected to illustrate the performance of the two NWP assimilation systems at locations where radiosondes are only launched once per day at 0000 UTC.

It can be seen from Table 5 that there is a substantial loss in accuracy in GASP_IWV estimates at 1200 UTC relative to 0000 UTC, as measured by rms or standard deviation. This we attribute to the lack of radiosonde reports available for assimilation at that

Table 3. Comparisons of RS_IWV with GASP_IWV and RS_IWV with ECMWF_IWV at 0000 UTC and 1200 UTC for the year 2000. Outliers omitted at the 3.5 standard deviation level. N is the number of comparison time points. IWV values are expressed in mm. ALIC and TOW2 statistics are only computed for 0000 UTC.

Site ID	*N*	*Ave RS_IWV*	*rms*	*Std dev*	*Mean bias*	*Std dev /Ave RS _IWV %*	*N*	*rms*	*Std dev*	*Mean bias*	*Std dev /Ave RS _IWV %*
	RS_IWV – GASP_IWV at 0000 UTC,1200 UTC						*RS_IWV – ECMWF_IWV at 0000 UTC,1200 UTC*				
COCO	711	43.1	3.5	3.4	-1.0	7.9	712	3.2	3.0	-1.1	7.0
DARW	731	41.0	3.0	2.9	-0.6	7.1	730	2.9	2.9	0.1	7.1
TOW2	365	32.6	3.1	2.8	-1.3	8.6	365	3.0	2.8	-1.1	8.6
KARR*	771	26.8	4.3	4.1	-1.4	15.2	726	4.0	3.8	-1.3	14.5
ALIC	364	19.7	2.5	2.4	-0.8	12.2	364	2.4	2.2	-0.9	11.2
YAR2	463	16.9	2.7	2.4	-1.3	14.3	462	2.6	2.3	-1.3	13.8
PERT	723	17.5	2.3	1.9	-1.2	10.9	717	2.8	2.1	-1.9	12.2
STR1	426	12.8	3.1	2.9	-1.2	22.6	424	2.6	2.5	-0.9	19.1
TID1	430	14.0	4.0	3.8	-1.2	27.1	431	3.7	3.6	-1.0	25.6
HOB2	713	14.4	2.0	1.6	-1.3	11.1	716	2.2	2.0	-1.1	13.6
MAC1	712	10.3	1.4	1.3	-0.7	12.3	712	1.4	1.3	-0.5	12.7
CAS1	692	3.6	0.7	0.6	-0.3	16.7	693	0.7	0.7	-0.1	19.9
MAW1	689	2.6	0.7	0.6	-0.4	22.8	690	0.5	0.5	-0.2	17.9
DAV1	705	3.0	0.7	0.7	-0.3	22.4	703	0.5	0.5	-0.2	15.8

* Radiosonde flights at times other than 0000 UTC and 1200 UTC were also available and used for KARR.

time. There is also a smaller loss in accuracy in ECMWF_IWV estimates. This may be explained by the generally higher accuracy of the more sophisticated ECMWF system analyses and possibly a more accurate calculation of ECMWF_IWV because they include an extra level at 925 hPa. Thus the additional GPS_IWV observations at 1200 UTC have the potential to substantially improve the accuracy of GASP and ECMWF analyses at these sites. At both of these sites the two assimilation-system-derived estimates at 1200 UTC predominantly overestimate relative to GPS, while Table 2 shows the tendency for the radiosondes to underestimate relative to GPS. A question arises as to why the numerical analyses are showing a moist bias relative to the radiosonde moisture data, when, over continental Australia, the radiosondes contribute the major source of moisture data available to the assimilation systems. Clearly, this is affected by other moisture information available for assimilation from either moisture sensitive radiance channels of the polar-orbiting satellites or short-range prediction, which data assimilation combines according to their respective reliabilities. Both the ECMWF and GASP systems use NOAA Advanced Television Infrared Observation Satellite Operational Vertical Sounder radiative data from the Advanced Microwave Sounding Unit and the High Resolution Infrared Radiation Sounder. Additionally ECMWF use Defense Meteorological Satellite Program microwave moisture-sensitive radiances in their system. However, such satellite data is used predominantly over the oceans, and thus the positive moisture biases relative to the radiosondes are likely to be due to biases in physics parametrisation, which condition the atmosphere of the assimilation systems to have a positive moist bias. The GPS versus analysis statistics for ALIC and TOW2 at 1200 UTC, when radiosondes are not available, highlight the effect of model physics as well as prediction error.

As a summary, but also to demonstrate graphically an application of GPS_IWV to NWP system performance monitoring, time series comparisons for January 2000 for four sites, COCO, DARW, ALIC and HOB2 are shown in Fig. 4. Here the number of comparison time-points at GPS sites has been adjusted to the number of radiosonde flights at 0000 UTC and 1200 UTC. For ALIC there are no 1200 UTC flights and thus no RS_IWV at that time. The time series in Fig. 4 show clearly the overall positive bias of the GPS_IWV relative to the other estimates, but also show again the high correlation of all estimates in their variability. Note that the outlier detection carried out for the pres-

Table 4. Comparisons of GPS_IWV with GASP_IWV and GPS_IWV with ECMWF_IWV at 0000 UTC and 1200 UTC for the year 2000. Outliers omitted at the 3.5 standard deviation level. N is the number of comparison time points. IWV values are expressed in mm.

Site ID	*N*	*rms*	*Std dev*	*Mean bias*	*N*	*RMS*	*Std dev*	*Mean bias*	*No. of RS*
	GPS_IWV- GASP_IWV				*GPS_IWV- ECMWF_IWV*				
COCO	723	4.1	4.1	0.4	720	3.2	3.1	0.3	707
JAB1	623	4.0	4.0	0.1	621	4.2	4.1	0.3	-
DARW	669	3.2	3.2	0.2	668	3.2	3.1	0.7	727
TOW2	727	4.0	4.0	-0.2	725	3.5	3.5	-0.5	726
KARR	691	4.1	4.1	0.3	688	3.6	3.6	0.4	724
ALIC	724	4.4	4.3	0.8	722	3.2	3.1	0.6	362
YAR2	590	2.4	2.4	0.3	591	2.4	2.4	-0.1	724
PERT	630	2.3	2.1	-1.1	628	2.8	2.1	-1.8	718
CEDU	717	3.4	3.4	-0.2	715	3.0	3.0	-0.2	-
STR1	713	4.0	3.7	-1.4	710	2.2	2.2	-0.3	728
TID1	554	2.5	2.4	-0.8	553	2.2	2.1	-0.8	728
BUR1	535	3.1	3.1	0.1	534	2.7	2.7	0.2	-
HOB2	716	2.1	1.9	1.0	711	2.2	1.9	1.1	728
MAC1	699	1.7	1.6	0.5	694	1.6	1.4	0.7	710
CAS1	708	1.8	0.9	1.6	690	2.0	0.9	1.8	687
MAW1	714	1.0	1.0	0.1	711	0.9	0.8	0.3	678
DAV1	646	1.7	1.0	1.4	635	1.7	0.9	1.5	700

Table 5. Comparisons of GPS_IWV with GASP_IWV and GPS_IWV with ECMWF_IWV at 0000 UTC and 1200 UTC for the year 2000. Outliers omitted at the 3.5 standard deviation level. N is the number of comparison time points. IWV values are expressed in mm.

Site ID	*Time UTC*	*N*	*rms*	*Std dev*	*Mean bias*	*N*	*rms*	*Std dev*	*Mean bias*	*No of RS*
		GPS_IWV – GASP_IWV				*GPS_IWV- ECMWF_IWV*				
ALIC	00	364	3.3	3.1	1.4	363	3.0	2.7	1.3	362
ALIC	12	360	5.3	5.3	0.3	359	3.4	3.4	-0.1	-
TOW2	00	364	3.4	3.4	0.6	363	3.1	3.0	0.8	363
TOW2	12	363	4.5	4.4	-1.1	362	3.9	3.5	-1.8	-

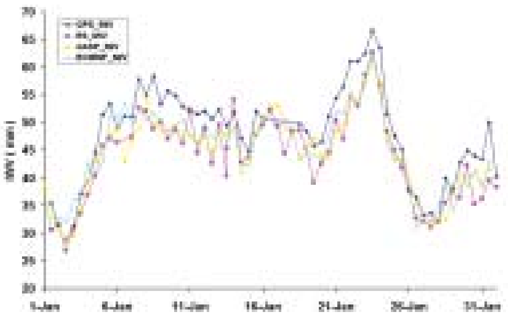
entation of the comparison statistics of Tables 3, 4 and 5, has not been applied to these plots. The big dips in RS_IWV in Fig. 4(b) at 0000 and 1200 UTC on 9 January 2000 are the result of radiosonde humidity sensor failures during these flights.

Comparison of IWV from radiosondes with GASP first guess

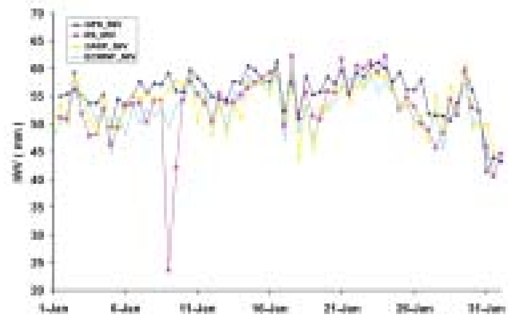
RS_IWV at 0000 UTC and 1200 UTC were also compared with GASPfg_IWV estimates to gauge the potential impact of GPS_IWV in the current ABM global assimilation. The relative average error measured as a ratio of standard deviation between GASPfg_IWV and RS_IWV relative to year 2000 average RS_IWV for stations other than Antarctica (CAS1, MAW1, DAV1) is 20.0 per cent which is larger than the equivalent 11.9 per cent error of GPS_IWV to RS_IWV estimation obtained from Table 2, column eight. In this comparison KARR, STR1 and TID1 relative errors between first guess statistics and RS_IWV statistics are larger than at other non-Antarctic sites (as in the case of the same

Fig. 4 Intercomparison of GPS_IWV, RS_IWV, GASP_IWV and ECMWF_IWV estimates during January 2000 for (a) COCO, (b) DARW, (c) ALIC and (d) HOB2. Estimates are produced for 0000 UTC and 1200 UTC, corresponding to the twice-daily radiosonde flights, except at ALIC where there is a single radiosonde launch at 0000 UTC each day. The obvious outliers at (b) DARW in RS_IWV are due to humidity sensor failures.

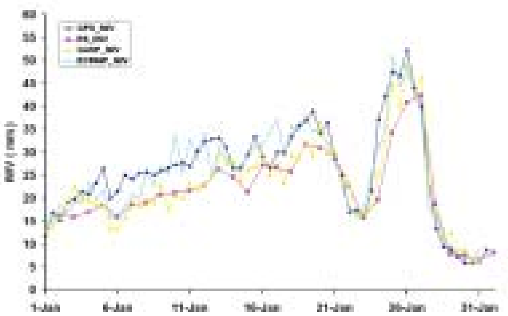
(a) COCO



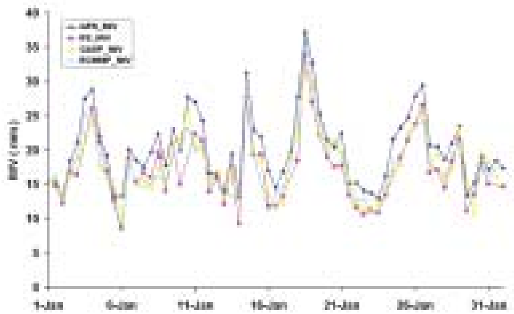
(b) DARW



(c) ALIC



(d) HOB2



stations' relative GPS_IWV and RS_IWV comparison in Table 2). This can be attributed to the large distance between the GPS and radiosonde or surface station sites, which adversely affects GPS_IWV accuracy at the GPS sites. Excluding these three sites, the comparisons between GASPfg_IWV and GPS_IWV errors relative to radiosondes are 18.0 and 8.8 per cent respectively. It thus points to potential benefits for GASP NWP system for both analyses and forecasts from assimilation of GPS_IWV data.

GPS_IWV diurnal variations

Substantial variability in atmospheric water vapour content is known to exist on both synoptic spatial scale and observing frequency time-scales. A detailed quantification of this variability for meteorological purposes is difficult without sophisticated instrumentation. High temporal frequency WVR and GPS data can provide an insight into higher frequency time-scales of IWV than that obtainable from radiosondes. Hogg et al. (1981), Rogers and Schwartz (1991), Güldner and Spänkuch (1999), Bouma and Stoew (2001) have all analysed such data for selected locations that did not include Australia and were able to isolate either high frequency mesoscale fluctuations or diurnal cycles in IWV. In Australia Dunsmuir and Phillips (1990) used 10 years of three-hourly observational data from 31 sites to examine and model temporal variations (annual, semiannual and diurnal cycles) in surface moisture mixing ratio, which is strongly correlated with IWV.

It is clearly desirable to have a capability for correct representation of diurnal variability in the hydrologic cycle in terms of amplitude and phase in the analysis and prediction of moisture in NWP systems. GPS derived diurnal variations as a function of both location and season should allow better verification of NWP system moisture accuracy. Therefore time series of hourly GPS_IWV estimates across the Australian region, which encompass a wide range of climatic conditions and capture substantial spatial IWV variability (Fig. 3), were used to investigate the presence of diurnal frequency variations in IWV. The mean diurnal GPS_IWV anomalies for the year 2000 were computed as described in Dai et al. (2002). Figure 5 shows these anomalies for five GPS sites and a clear diurnal variation in IWV of 1 to 2 mm amplitude may be seen. Most of these variations are easily seen to have a similar phase response across continental Australia, with morning minima between 0700 and 0800 and late afternoon maxima between 1500 and 1800 local solar time.

The occurrence of a systematic diurnal IWV cycle at inland sites such as ALIC is attributed to a naturally occurring solar-driven cycle of moisture enhancing evapotranspiration, usually peaking between mid-morning and mid-afternoon local solar time, slowing down in late afternoon, followed by drying of the atmosphere by gradual cooling and dew formation in the evening and overnight. Patterns like this are more difficult to isolate in locations of substantial horizontal air movements and unstable weather such as COCO, which is not shown, where the yearly averaged diurnal signal is weaker. Coastal sites such as DARW have their daily cycles affected by oceanic moisture supply, land-sea contrast driven convection and sea or land breezes. Higher latitude sites such as MAC1 and those in Antarctica are characterised by an apparent semidiurnal cycle in yearly averaged data, an effect which is in part due to the length of solar day in high latitudes. Although a semidiurnal cycle has also been detected for TOW2, it is not shown.

Amplitudes of diurnal variations vary with the level of moisture content, with diurnal temperature range and are dependent on geographical location (Fig. 5), being generally larger in the moist tropics and smaller in dry inland locations or higher latitudes. Figure 5 also indicates that the amplitude of the diurnal signal is usually substantially lower than the amplitude of day-to-day variations in IWV as seen for corresponding stations in Fig. 2.

The apparent similarities in the diurnal variation characteristics over similar geographical areas may be helpful in validating IWV from NWP systems at locations where there are no GPS stations, but for which the diurnal variations may be approximated from those known at other GPS locations. Furthermore, it can be seen in Fig. 5 that the mean hourly rate of change in GPS_IWV varies during the day and from site to site. At most sites it is most rapid during morning hours when there is a sharp increase in surface temperature. This information may be useful when choosing a time-window for the assimilation of moisture observations from low temporal frequency measuring instruments such as radiosondes.

GPS_IWV and thus the amplitude of its diurnal variation at a given location depend on ZWD and T_m, which are functions of surface pressure and temperature, variables that also have diurnal variations. Quantifying the magnitude of GPS_IWV diurnal variation amplitude, given the amplitudes of surface pressure and temperature, is not straightforward due to interdependence of all three parameters and to other factors that affect ZWD and T_m independently. By fixing ZWD in Eqn 3 for a given T_s and using different T_m models, we have found a dependence of the amplitude of GPS_IWV variations on the assumed model for the (T_m, T_s) relationship. In the case of the regression model in Eqn 6, sensitivity is dependent on the regression slope, which effectively scales the diurnal cycle amplitude. Our initial local estimation of (T_m, T_s) regression, using 23 years of soundings for DARW is, $T_m = 208.66 + 0.27T_s$. However $T_m = 153.75 + 0.448T_s$ for just year 2000 soundings data. For PERT, T_m = $104.54 + 0.612T_s$ and $115.9375 + 0.57T_s$ for just year 2000 soundings data. Locally derived regression models indicate that in the case of DARW, the regression slope should be lower for that site, and thus the respective diurnal amplitude smaller. GPS_IWV values could consequently be revised upwards by nearly 0.6 mm when the corresponding T_s is low, and downwards by almost 0.2 mm when T_s is high. On average the DARW GPS_IWV would slightly increase, but the amplitude of diurnal variations would slightly decrease. A clearer picture of diurnal variations could be gained with further reduction in the uncertainty in the estimation of T_m and when using GPS_IWV data from time series that are longer than a single year. This is intended in a subsequent study.

Because derived diurnal variations in GPS_IWV data are relatively small and could be induced only by diurnal variations in temperature (T_s and thus T_m), another GPS moisture dependent variable ZWD was examined for the presence of diurnal variations, as it is free from temperature effects in GPS data processing. Figure 6 shows anomalies in ZWD for the same sites as in Fig. 5. It can be seen that the GPS_IWV and ZWD anomalies have very similar variability at each of the five sites considered. This suggests that variations in GPS_IWV, and implicitly in PW, are most likely real and not due to a T_m artifact.

Factors influencing GPS_IWV accuracy

In the various comparisons considered here, the GPS_IWV estimation accuracy was assessed by comparing GPS_IWV estimates with the independent IWV estimates from radiosondes and NWP systems.

Fig. 5 Year 2000 mean diurnal GPS_IWV anomalies at selected GPS locations

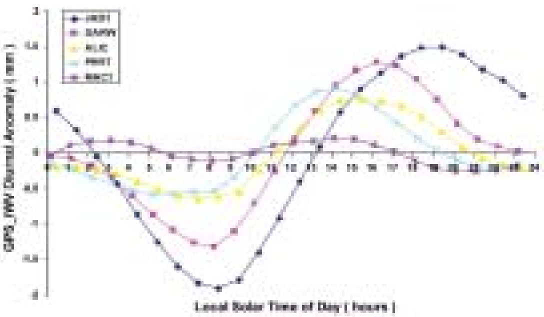
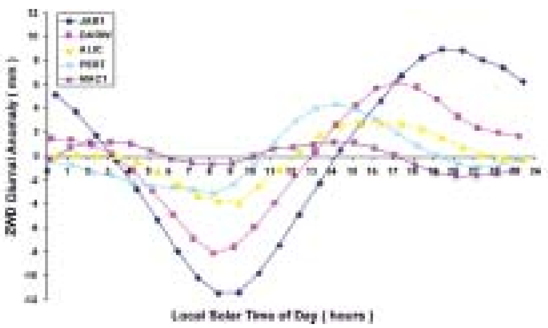


Fig. 6 Year 2000 mean diurnal GPS ZWD anomalies at selected GPS locations



The inaccuracies of radiosonde-derived water vapour products have long been known to be at the 5 per cent or more level, approximately 1.5 mm of the global average IWV (Keihm 2001). The inaccuracies are partly due to systematic biases, and unless these are accurately known, validation of GPS_IWV estimates against radiosondes will not be better than this level, even if GPS_IWV estimates are more accurate than RS_IWV estimates. That is assuming their errors are uncorrelated. Therefore, we now discuss three factors that influence the relative accuracies, namely inaccuracies in radiosonde estimates due to dry biases, GPS data processing inaccuracies and errors in the adoption of a T_m model generated from data not local to the site considered. It is also of note that independent research of van der Hoeven et al. (1998) has demonstrated that GPS_IWV estimation has an accuracy that is at least comparable to that of radiosondes and WVR measurements; of those two, WVR measurements are considered to be of somewhat higher accuracy.

Effect of radiosonde dry bias

Recent findings of dry biases in Vaisala RS80-A measurements of relative humidity (Wang et al. 2002; Leiterer et al. 2005; Nakamura et al. 2004) suggest a better agreement between RS_IWV and GPS_IWV is likely than indicated by Table 2. We estimated dry bias corrections (see Appendix) for the radiosonde sites used in this study using data from flights in the year 2000. We followed the method of Wang et al. (2002), but tailored it to the Vaisala RS80-A radiosonde and to the standard processing of radiosonde data in Australia. This meant omitting the contamination, basic calibration model and measured ground check error corrections used by ibid. For comparison, dry bias corrections estimated according to Leiterer et al. (2005) are also shown in the Appendix. These corrections would substantially reduce the mean differences between GPS_IWV and RS_IWV in Table 2 and would also contribute to the reduction of rms errors. Recent comparisons using data collected in Poland (Brzoska et al. 2004) found that the Leiterer et al. (2005) corrections performed somewhat better than those of Wang et al. (2002). Nakamura et al. (2004) tested three correction methods on data collected in Japan and found that the method of Leiterer et al. (2005) accounted for a smaller fraction of the Vaisala RS80-A dry bias relative to the other two methods, including that of Wang et al. (2002). Given those discrepancies in correction methods and their outcomes, and the lack of unbiased IWV reference estimates (from WVR or the new more accurate Vaisala RS90 radiosonde) in our study, we did not recalculate Table 3 values with the above-mentioned corrections.

Another consideration was that GPS_IWV estimates in this study were calculated using (T_m, T_s) regression, and so indirectly radiosonde moisture data (Eqn 5 for T_m uses water-vapour partial-pressure e) that were not corrected for the dry bias when used to derive this regression. NWP system analyses and forecasts in our comparisons also used uncorrected radiosonde data.

Effect of data-processing software

Each step of the GPS ZTD retrieval process is performed with a certain degree of uncertainty and each introduces its own instrumental, procedural and computational errors, such as those associated with GPS antennas, receivers and with processing algorithms and strategies adopted by the data analyst and also IGS Analysis Centres. Each of these steps is being continually refined by the GPS geodetic research community, which results in smaller errors. Furthermore, this study was undertaken during a time of high ionospheric activity. The eleven-year sunspot cycle peaked in 2000; as such 2000 represents the most pessimistic scenario regarding GPS_IWV quality. The retrieval and conversion procedures also rely on data such as corrections for ocean tide loading, derived from instruments other than GPS receivers, and these contribute their own uncertainties.

The current knowledge of error statistics of GPS ZTDs in a meteorological context is limited. The GPS estimation of atmospheric delay parameters was performed in this study using the Bernese software. Other popular geodetic software, notably GIPSY from the Jet Propulsion Laboratory, California Institute of Technology and GAMIT from Massachusetts Institute of Technology use similar models and methods to compute the tropospheric delay, so comparisons with such estimates provide other means of quality control. For instance, Feng et al. (2003) used GAMIT and obtained accuracies similar to those in this study. The IGS tropospheric product, namely the combination of ZTDs from (then) seven different IGS Analysis Centres that used various geodetic GPS software packages, can also be used for quality control, although these are only produced with a two-hour temporal frequency. As an illustration of the quality of the IGS tropospheric product over the year 2000 for the sites in this study, Table 6 lists the rms, standard deviation and bias of IGS derived GPS_IWV compared with RS_IWV. Recalling Table 2, it can be seen that GPS_IWV derived from the IGS tropospheric product and the Bernese software used in this study are very similar.

As mentioned earlier, relative constraints of 2 mm were applied between adjacent tropospheric estimates for tropospheric delay estimation as these were found to be a reasonable 'generic optimum'. From a GPS perspective, different constraints may be more appropriate for some sites than others and the choice may also depend on the atmospheric activity. Assigning ‘dynamic’ constraints in software such as Bernese is, at present, extremely difficult. Before choosing the 2 mm constraint, we varied the constraint from no constraint down to 1 mm, and obtained very similar results for 1 mm and 2 mm constraints. Overall, if the constraint is too loose, occasional large spurious spikes in ZTD arise. If the constraint is too tight, the estimates are over-smoothed and are not sensitive to more rapid atmospheric changes that may be of interest.

The effect of mean atmospheric temperature on the model

It follows from Eqns 3 to 6 that given the ZWD estimate, the mean temperature model used and the accuracy of the temperature estimate at the GPS site are the main factors affecting GPS_IWV determination accuracy. For greater accuracy, models for T_m are sometimes derived locally and allow for seasonal variations. However, Mendes et al. (2000) concluded that ‘regionally-optimized models do not provide superior performance compared to the global models’ as ‘there is little gain in tuning the models for a particular region, as regards the mean bias, and almost no gain in reducing the rms scatter’ in T_m. Two of the Mendes ‘global’ mapping functions ($T_m = 50.4 + 0.789T_s$ and $T_m = 196.05 + 0.000003402T_s^3$) tested here, for the DARW and PERT data, yielded GPS_IWV consistent with those produced using Eqn 6, while our locally derived regressions for these sites yielded GPS_IWV more consistent with those based on the Ross and Rosenfeld (1997, 1999) local formulae, with Guam used as a proxy for DARW.

Table 6. Differences between GPS_IWV derived from the IGS tropospheric product and RS_IWV for the year 2000. Outliers omitted at the 3.5 standard deviation level. Error values are expressed in mm.

Site ID	*No of comparison data points*	*rms*	*Std dev*	*Mean bias*	*Std dev / Ave RS_IWV (%)*
COCO	693	3.2	2.2	2.4	5.1
DARW	638	3.3	2.7	1.9	6.5
TOW2	353	3.3	1.9	2.7	5.9
KARR	707	5.4	4.9	2.3	18.6
ALIC	334	2.9	1.6	2.4	8.4
PERT	645	1.5	1.5	0.2	8.5
HOB2	687	2.0	1.0	1.8	7.0
MAC1	665	1.7	1.0	1.3	9.8
CAS1	455	1.9	0.4	1.8	14.7
MAW1	669	1.1	0.6	0.9	24.0
DAV1	516	1.6	0.4	1.5	15.4

Feng et al. (2003) compared T_m estimates derived from radiosonde data for July-September 2000 for five Australian GPS sites and from the regression model of Bevis et al. (1992), obtaining very similar results for both methods. Infrequent and sparse radiosonde reports are, however, less practical for estimation in real-time hourly applications. Vey et al. (2004) report (after Schuler 2001; Bevis et al. 1994) that using site specific T_m derived from NWP systems rather than a global relation reduces the IWV relative error from 2 to 1 per cent. For assimilation of GPS_IWV observations into a NWP system, direct T_m estimation from NWP system outputs should be considered.

Conclusions

The quality of GPS_IWV across the Australian region has been assessed using data for the whole of 2000 from seventeen sites distributed across a wide range of climates. For eight GPS sites (COCO, DARW, TOW2, ALIC, YAR2, PERT, HOB2, MAC1) either co-located or close to (average separation of 24 km) radiosonde launch sites, an average error of GPS_IWV relative to RS_IWV estimation standard deviation was 8.8 per cent. This error would be somewhat smaller if all GPS sites were co-located with surface weather stations and radiosonde sites. Furthermore, mean biases found in GPS_IWV estimates relative to RS_IWV estimates would be further reduced if RS_IWV estimates were corrected for the dry bias in the Vaisala RS80-A relative humidity measurements. For Antarctica the GPS_IWV standard deviation errors were found to be about 18 to 21 per cent, which is a relatively large value.

The ABM NWP system six-hour forecasts, used as a first guess in operational data assimilation, were found to have relative IWV errors with respect to radiosondes of 20.0 per cent for all radiosondes in this study except for those in Antarctica in the year 2000 data. Since GPS_IWV estimates can be obtained during all weather conditions and have a high temporal frequency, timely and accurate GPS moisture observations, when converted to proxies for moisture profiles in NWP assimilation, have the potential to reduce IWV errors. Modest positive impacts have already been noted elsewhere in the world, as detailed by Gutman et al. (2004) for continental USA. The sites ALIC and TOW2, where radiosondes are only launched once per day at 0000 UTC, well illustrate the potential benefit resulting from the assimilation of higher temporal frequency GPS moisture data. The 1200 UTC GASP_IWV estimates were clearly shown to be less satisfactory than those for 0000 UTC reflecting the absence of radiosonde data at this time. Since early 2004 the ABM is launching radiosondes predominantly at 0000 UTC, with occasional 1200 UTC radiosondes on an *ad hoc* basis.

In addition, the following conclusions, outlooks and recommendations can be made:

- GPS offers a promising total column water vapour estimation system for the Australian region.
- The comparison of GPS and radiosonde derived IWV indicates accuracies similar to those reported in previous studies and these accuracies validate the applied methodology and software used to derive GPS_IWV. Relative accuracies of GPS_IWV estimates with respect to radiosondes show dependence on the amount of atmospheric moisture. Standard deviations are larger in the tropics and small in Antarctica. Further study of the accuracy of GPS_IWV estimates, particularly biases relative to RS_IWV, is recommended. It would be desirable to compare GPS_IWV against additional independent measurements of IWV, such as available from the more accurate WVRs. Issues regarding the GPS processing technique require investigation and refinement, particularly the treatment of new antenna phase centre models and mapping functions currently under development.
- GPS_IWV can be used for monitoring the performance of data assimilation and prediction systems over an extended period of time and on a daily basis. Relevant comparisons may be used for detecting moisture biases in NWP systems.
- The GPS_IWV estimation accuracy warrants its use in the ABM assimilation systems, except at this time, for Antarctica. Furthermore, direct assimilation of ZTD or ZWD is also warranted and possibly more preferable given that it is unaffected by the issues in estimating T_m. Despite their small number, GPS moisture estimates have potential to enhance moisture analyses in data assimilation because of the relatively low spatial and temporal frequency of the current radiosonde network across the Australian region.
- Significant diurnal GPS_IWV variations were found to exist at most of the GPS sites across the Australian region, which have not been reported previously because radiosonde measurements at 0000 UTC and 1200 UTC are not able to represent the amplitude or phase of the diurnal cycle. The amplitude of the GPS-based estimate of the diurnal cycle is clearly dependent on the (T_m,T_s) regression accuracy.
- ZTD was converted to IWV using surface temperature data as the input to a regression model developed to replicate the mean atmospheric temperature obtained from radiosonde profiles across the

USA. The derivation of local mean atmospheric temperature models should be undertaken.
- This validation study used IGS 'final' orbits (available with a latency of approximately 13 days). However, since the IGS real-time orbital product and the IGS Ultra Rapid Orbit has been shown (Dousa 2001) to provide similar quality results to post-processed applications, the operational application of near real-time GPS_IWV in the ABM NWP data assimilation system should now be feasible. Implementing such a system operationally will depend on the successful demonstration of the use of the GPS_IWV estimates in the current assessment experiments and the testing of the quality of real-time orbits across the Australian region.

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Appendix

Average RS_IWV corrections resulting from dry bias corrections to year 2000 radiosondes’ relative humidity (RH) reports. Two correction methods compared: ‘W’, after Wang et al (2002); ‘L’, after Leiterer et al. (2005). RS_IWV estimates were done and corrections computed for GPS sites from nearby radiosonde data. ‘W’ corrections include age corrections for the Vaisala RS80-A sensor. If corrections are applied RS_IWV values should be revised upwards.

GPS ID	*‘W’ RH correction (mm IWV)*	*‘L’ RH correction (mm IWV)*	*No of cases*	*RS station number*	*RS average (years)*
COCO	1.14	2.50	718	200284	0.61
DARW	1.08	2.36	735	14015	0.65
TOW2	1.35	1.90	368	32040	1.00
KARR	1.06	1.58	808	4032	0.83
ALIC	1.02	1.13	366	15590	0.64
YAR2	0.99	0.97	466	8051	0.66
PERT	1.00	1.00	730	9021	0.70
HIL1	1.00	1.02	730	9021	0.70
STR1	0.83	0.75	432	72150	0.65
TIDB	0.86	0.80	432	72150	0.65
BUR1	0.89	0.86	728	72150	0.65
HOB2	0.88	0.84	728	72150	0.65
MAC1	0.70	0.60	725	300004	0.86
CAS1	0.42	0.22	705	300017	0.95
MAW1	0.38	0.16	698	300001	1.03
DAV1	0.39	0.19	714	300000	0.99