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Evaluating Regional Atmospheric Water Vapour Estimates Derived from GPS and Short-Range Forecasts of the Canadian Global Environmental Multiscale Model in Southern Alberta

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ABSTRACT *Integrated atmospheric moisture has been derived from a network of Global Positioning System (GPS) receivers established in southern Alberta. GPS receivers and post-processing techniques provide the ability to estimate integrated precipitable water vapour (PWV) at temporal and spatial scales not usually available using conventional observational techniques and without costly expendables. GPS-derived PWV was evaluated during the Alberta GPS Atmospheric Moisture Evaluation (A-GAME) using nearby radiosonde observations from the Airdrie, Olds-Didsbury and Sundre airports during field campaigns in the summers of 2003 and 2004. For the 2004 A-GAME period, the regional (15 km) Global Environmental Multiscale model (GEM)-modelled PWV was compared to the GPS derived PWV using a distance weighting approach. GEM model performance was assessed with regards to prognosis time (from 0 to 9 hours), grid cell elevation, location and the presence of storms in the study region. The results show that there is good agreement between radiosonde-derived PWV and PWV derived from nearby GPS sites with correlations (r^2) ranging from 0.76 to 0.84; the GPS-derived PWV showed a small dry bias averaging 0.6 mm. When compared to GPS-derived PWV, GEM model performance was found to be favourable out to the hour-3 prognosis with an overall correlation (r^2) of 0.63. Performance decreased with increasing prognosis time and as a result of the presence of storm activity in the study region but did not decrease with increasing grid cell elevation.*

RÉSUMÉ *[Traduit par la rédaction] L'humidité atmosphérique intégrée a été dérivée à partir d'un réseau de récepteurs GPS (système mondial de localisation) établi dans le sud de l'Alberta. Grâce aux récepteurs GPS et à des techniques de post-traitement, il est possible d'estimer la vapeur d'eau précipitable (VEP) intégrée à des échelles spatiales et temporelles que ne permettent habituellement pas les techniques classiques d'observation et sans employer de coûteux dispositifs non récupérables. La VEP dérivée par GPS a été évaluée lors du projet Alberta GPS Atmospheric Moisture Evaluation (A-GAME) au moyen d'observations par radiosonde faites à proximité, aux aéroports de Airdrie, Olds-Didsbury et Sundre, pendant les études sur le terrain menées au cours des étés de 2003 et 2004. Pour la période A-GAME de 2004, la VEP modélisée par le GEM (modèle global environnemental multi-échelle) régional (15 km) a été comparée à la VEP dérivée par GPS à l'aide d'une technique de pondération en fonction de la distance. La performance du GEM a été évaluée par rapport à la portée de la prévision (de 0 à 9 heures), à l'altitude de la maille de la grille, à l'endroit considéré et à la présence d'orages dans la région à l'étude. Les résultats montrent que la VEP dérivée des sondages concorde bien avec la VEP dérivée des sites GPS à proximité, avec des corrélations (r^2) allant de 0,76 à 0,84; la VEP dérivée par GPS a affiché un léger biais sec de 0,6 mm en moyenne. Par comparaison à la VEP dérivée par GPS, la performance du GEM s'est révélée favorable jusqu'à la prévision pour l'heure 3, avec une corrélation générale (r^2) de 0,63. La performance a diminué à mesure que le temps de prévision augmentait et lorsqu'il y avait de l'activité orageuse dans la région à l'étude, mais elle n'a pas diminué à mesure qu'augmentait l'altitude de la maille.*

1 Introduction

A Global Positioning System (GPS) is an all-weather, global navigation satellite system that continuously transmits L-band radio frequency (RF) signals (L1 frequency is 1575.42 MHz and L2 frequency is 1227.60 MHz) from a constellation of a minimum of 24 satellites (Parkinson and Spilker, 1996). The GPS signal's code and carrier phase

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information are used to determine ranges from a receiver to at least four (and typically six to eight) satellites. This information is then used to estimate the precise location of the GPS receiver. Range derivations are based on the assumption that the electromagnetic waves propagate at the speed of light. However, as the signal passes through the Earth's atmosphere, both the troposphere and the ionosphere contribute to range errors. Additional sources of error include orbital errors, satellite and receiver clock errors, receiver noise, multipath (the reception of indirect or reflected GPS signals) and satellite differential L1-L2 frequency biases. It was shown by Coster et al. (1990) that tropospheric and ionospheric path delays could be estimated from GPS observations provided that these additional errors were mitigated. Further to this, Bevis et al. (1992), Rocken et al. (1993) and Businger et al. (1996) demonstrated that errors derived from the GPS signal propagating through the atmosphere could be used to estimate the integrated amount of moisture present in the atmosphere along the ray path of the GPS signal.

The magnitude of the tropospheric delay directly over a receiver, the zenith tropospheric delay (ZTD), has an approximate signal path length of 2 to 3 m (i.e., the signal is delayed by the amount of time that light takes to travel this distance) and is primarily due to the presence of the neutral (dry) atmosphere. This portion of the delay, called the Zenith Hydrostatic Delay (ZHD), can be modelled with an accuracy of 1 to 2 mm provided precise surface pressure (±0.1 hPa) data are available (Bevis et al., 1992). The remaining component is known as the zenith wet delay (ZWD) and is related to the presence of atmospheric water vapour. The magnitude of the ZWD typically ranges from a few centimetres to several tens of centimetres. It is the ZWD component, estimated from GPS observations, that is related to precipitable water vapour (PWV) using a dimensionless conversion factor ($\prod$) defined by Bevis et al. (1994), which is a function of surface temperature.

The relative accuracy of GPS techniques to estimate PWV, in conjunction with the proliferation of GPS reference networks, has prompted the use of GPS as a new and innovative tool to measure water vapour worldwide (Rocken et al., 1997; Rocken et al., 2000; Ware et al., 2000; Jerrett and Nash, 2001). There are several advantages to using GPS over conventional techniques such as radiosondes for estimating PWV. These advantages include cost (as there are no expendables required and equipment costs are relatively low) and data resolution. Radiosonde observations are typically made only twice daily at 00:00 and 12:00 UTC within a sparse upper-air observation network (the only site in Alberta is located at Stony Plain). However, GPS receivers are capable of operating continuously in all weather conditions producing water vapour estimates at resolutions up to 15 minutes (96 estimates daily). This temporal resolution, combined with low-cost equipment installed in a network configuration, provides the ability to estimate regional PWV trends not possible with radiosondes. GPS networks are now deployed all over the world and since they have become a reliable tool for measuring PWV, the integration of these observations into some numerical weather prediction (NWP) models has shown promise for improved weather forecasting and climate monitoring (Kuo et al., 1993; Naito et al., 1998; Gutman and Benjamin, 2001; Cucurull, 2001).

Water vapour radiometers can also be used to determine PWV. They are accurate to ±1 mm of PWV derived from GPS and radiosonde observations (Niell et al., 2001). While radiometers provide a means of obtaining continuous observations, they can be adversely affected by inclement weather conditions, and it is still cost-prohibitive to install the instruments in a network of stations.

NWP model output, such as that derived from the Global Environmental Multiscale (GEM) short-range regional forecast model used by Environment Canada, is yet another option for the estimation of regional atmospheric water vapour where there are no observations. A detailed model description can be found in Mailhot et al. (1997) and Côté et al. (1998). The GEM regional model is currently initialized twice daily (at 00:00 UTC and 12:00 UTC) producing 48-hour forecasts. The current version of the GEM regional model has been operational since May 2004 and has a horizontal resolution of 15 km with 58 vertical levels, replacing a previous version which had a horizontal resolution of 24 km with 28 vertical levels. An analysis output is produced every six hours after initialization and consists of a combination of assimilated observed data (surface, upper-air and remotely sensed) and a six-hour GEM forecast valid at the current analysis time, initialized with the previous analysis fields (Laroche et al., 1999). GPS-derived PWV is not currently assimilated into this version of the operational GEM model. This source of atmospheric water vapour information has been used for atmospheric research applications such as atmospheric moisture budgets (Strong, 1997) and basin water balance work (Strong et al., 2002) but the accuracy of these products is limited by the sparseness of surface and upper-air observations, the model's assimilation scheme, model physics and resolution. The assimilation of GPS-derived PWV has the potential to increase the accuracy of GEM regional moisture fields for both forecasting and research purposes (Deblonde et al., 2005). GPS-derived data can also be employed as a verification tool to assess the performance of GEM in resolving PWV fields. This could be extremely valuable considering that gridded GEM data are frequently employed for research and operational purposes where conventional observations are sparse. It is important to recognize and quantify inherent biases in the GEM PWV output that may result from complex topography (i.e., degradation in model performance with increasing model elevation and topographical smoothing) or unresolved atmospheric or surface processes (including evaporation/evapotranspiration, convection, cloud and precipitation processes).

Previous intercomparisons between GPS- and radiosonde-derived PWV are numerous and have shown relatively good agreement between the two retrievals. Deblonde et al. (2005) provide a comprehensive list of references that report the standard deviation of the difference (henceforth called SD) between radiosonde-derived and GPS-derived PWV ranging from 1.4 to 2.6 mm. Ohtani and Naito (2000) report a GPS dry bias of 2.7 mm while Coster et al. (1996) report a GPS wet bias of 1.80 mm. Other reported SDs vary between 1.35 mm (Coster et al., 1996) and 2.21 mm (Köpken, 2001). Deblonde et al. (2005) show their four-month intercomparisons of eight Natural Resources Canada (NRCan) GPS receivers co-located with (or near to) radiosonde sites. The reported statistics show an average correlation coefficient (r^2) of 0.94 and an average bias (GPS minus radiosonde) of 1.4 mm with an SD of 2.0 mm (GPS wet bias). They also report a seven-month intercomparison between 66 International Global Navigation Satellite System (GNSS) Service (IGS) sites co-located with (or near to) radiosonde sites with an average correlation, bias and an SD of 0.96, 0.7 mm, and 2.6 mm, respectively (GPS wet bias). Yang et al. (1999) reported similar results for intercomparisons in Finland and Sweden (similar climate to that of Canada) with r^2 ranging from 0.88 to 0.94 but with a GPS dry bias, estimated graphically, of approximately 1 mm. In addition to this, Smith et al. (2001) co-located a GPS receiver with the operational radiosonde station at Ft. Smith, NT during the summer of 2000 and reported correlation coefficients (r^2) of 0.96 with an average dry bias in the GPS-derived PWV of 0.5 mm and an SD of 1.4 mm.

Deblonde et al. (2005) also report statistics for intercomparisons between NRCan and IGS GPS receivers and GEM analyses and 6-hour forecast PWV. The model resolution during this analysis was 0.9° (approximately 100 km) with 28 vertical levels. Correlations between the model and GPS-derived PWV were very similar to those of the model-radiosonde intercomparison. The bias (GPS-GEM) for the analysis output varied from 0.7 (IGS) to 1.2 mm (NRCan) with an SD between 2.0 (NRCan) and 3.5 mm (IGS). For the forecast intercomparison, the bias varied from 0.5 (IGS) to 1.0 mm (NRCan) with an SD of 2.2 (NRCan) to 3.6 mm (IGS). The SD for the forecast intercomparison was larger than the SD from the analysis intercomparison.

Previous intercomparisons between GPS-derived, GEM-modelled, and radiosonde-derived PWV, as briefly outlined, show that GPS-derived PWV would be extremely useful in meteorological forecasting, atmospheric research and monitoring and NWP model verification. In this paper, we will use data from a network of GPS receivers throughout southern Alberta, assess their accuracy for estimating regional PWV, and then apply these data to assess GEM model analysis and forecast products. The GPS network in southern Alberta, combined with the complex topography and dynamic regional PWV fields during the summer months, provides a unique opportunity for examining GEM performance in a region where no other sources of PWV information exist.

The study region and the characteristics of the data used in this research, including GPS, radiosonde, and GEM data, are described in Section 2. Section 3 outlines the intercomparison results for GPS-derived versus radiosonde-derived PWV and GEM-modelled versus GPS-derived PWV. The results are elaborated on in Section 4 which also offers some discussion on error sources and how these results compare with those documented by other researchers. Section 5 highlights the results of this research and provides some concluding remarks.

2 Data acquisition and processing

a *The Southern Alberta GPS Network*

The installation of the southern Alberta Network (SAN) of GPS sites (Fig. 1) began in the spring of 2003. The GPS sites were installed with baselines of approximately 50 km which make them ideally suited to monitoring mesoscale atmospheric moisture dynamics. Many of the GPS receivers were co-located with Paroscientific MET3A meteorological instrumentation to measure surface pressure and temperature. The Alberta GPS Atmospheric Moisture Evaluation (A-GAME) campaign was conducted during the summers of 2003 and 2004. The main objective of A-GAME was to use conventional radiosonde measurement techniques to asses the capability of the Alberta GPS network to estimate PWV accurately. Radiosonde observations were taken at the Airdrie, Olds-Didsbury and Sundre airports from 16–26 July 2003 and from the Airdrie and Olds-Didsbury airports from 12–16 July 2004. The radiosonde sites are indicated by stars on Fig. 1 and their locations differ somewhat from the GPS locations. The Airdrie and Sundre radiosonde sites are 31 m higher than their neighbouring GPS receivers and the Olds radiosonde site is 8 m lower than the neighbouring GPS receiver. For clarity during intercomparisons, the airport radiosonde sites will be abbreviated to AirdRS, OldsRS and SundRS to identify the sites at Airdrie, Olds-Didsbury and Sundre, respectively. The GPS network configuration of 2003 was changed somewhat for 2004 and the two configurations, with site information, are listed in Table 1. Water vapour radiometer data would have been useful for the intercomparisons but unfortunately no radiometer data were available for this analysis.

b *GPS Data*

GPS sites in the SAN are equipped with Novatel Modulated Precision Clock (MPC) receivers and Novatel 600 series antennae; data are collected continuously every 1 s. During A-GAME 2004, a temporary Ashtech μZ receiver was deployed at Limestone Mountain in west-central Alberta in order to detect dryline development (known to be important in the initiation of severe thunderstorms in Alberta) coming across the mountains. Many of the Novatel GPS sites were co-located with Paroscientific meteorological instruments that logged pressure, temperature and relative humidity directly to the GPS receiver every 30 s. These instruments, according to the manufacturer, have accuracies of ±0.08 hPa, ±0.1°C, and ±2% for pressure, temperature and RH, respectively. Other sites were equipped with similar instrumentation (with similiar accuracies) and recorded by Campbell Scientific data loggers.

Hourly ZTD estimates were obtained after post-processing the GPS data with Bernese V5.0 Software (Hugentobler et al.,

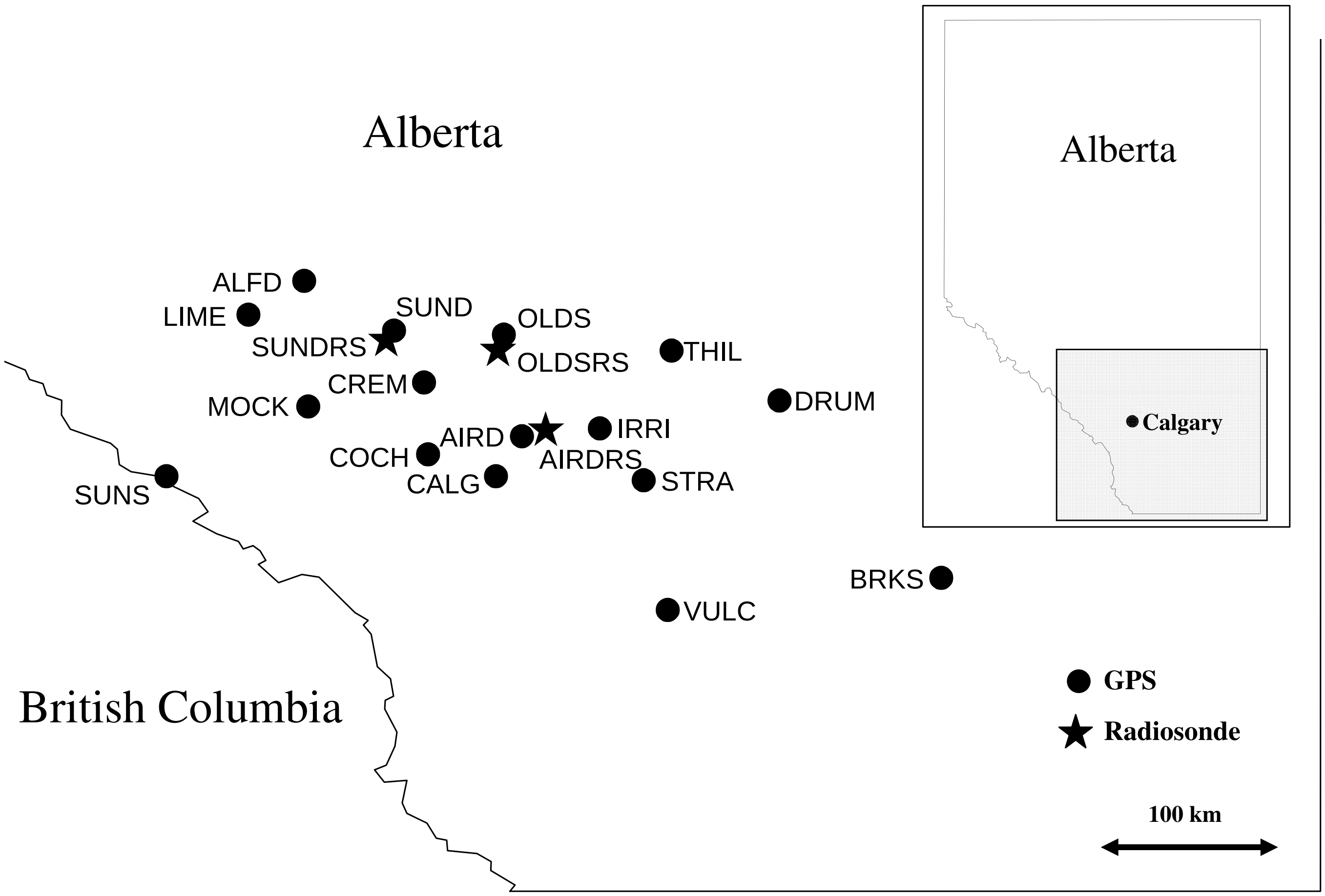


Fig. 1 The southern Alberta GPS and radiosonde network during A-GAME. The 2003 and 2004 GPS sites are listed in Table 1.

2001). The network data were first processed to determine precise GPS site coordinates. To obtain high-accuracy ZTD estimates, these precise coordinates were used as well as final IGS orbit products and antennae phase centre information from the manufacturer. Since atmospheric errors are spatially correlated, long-baselines were formed in the network processing to ensure that absolute ZTD estimates were retrieved. The network processing incorporated data from several IGS reference sites, specifically Algonquin, Ontario (ALGO), Penticton, British Columbia (DRAO) and North Liberty, Iowa (NLIB). Satellite and receiver clock biases are mitigated by double-differencing observations between two satellites and two receivers.

In order to minimize the likelihood of erroneously including GPS signals reflected off nearby surfaces, also referred to as multipath, an elevation angle mask of 5 degrees was applied for the GPS observations. Observations were weighted according to their zenith angle, z, in the estimation process with a $1/\cos(z)^2$ function. In addition, the neutral atmospheric effect was assumed to be azimuthally symmetric and a dry Niell mapping function (Niell, 1996) was applied. A least-squares batch adjustment provides the hourly batch estimates of ZTD and standard error. ZTD values with a standard error greater than 1 mm were rejected.

The ZHD is estimated as a function of surface pressure according to the Saastamoinen model (Saastamoinen, 1972) and subtracted from the ZTD. The remaining zenith wet delay is converted to PWV using Π. The PWV mean and SD for each site during A-GAME 2004, days 193 to 200, are shown in Fig. 2. The mean values range from 20.6 mm at Three Hills (THIL) to 9.3 mm at the Sunshine Mountain (SUNS) site. The mean PWV for all of the sites analyzed from A-GAME 2004 is 16.5 mm with a SD of 4.6 mm.

c *Radiosonde Data*

Radiosonde profile data were obtained using Vaisala RS-80G radiosonde instruments at OldsRS and AirdRS in 2003 and 2004 and Airsonde (AIR-3A) instruments at SundRS in 2003 only. The radiosonde intruments measure pressure, temperature, relative humidity, wind speed and wind direction every two seconds (except at SundRS where wind speed and direction were derived using an optical theodolite at five-second intervals). During post-processing, the high resolution data were interpolated to 5 hPa levels and the water vapour mass (kg m^{-2}) was derived for each layer and accumulated through the column. The total water vapour mass in the column expressed in kg m^{-2} is numerically equivalent to the depth of PWV in the column in millimetres.

TABLE 1. GPS and radiosonde sites in the SAN during A-GAME (sites active in 2003 and 2004 are marked with an X, site abbreviations are in parentheses).

Site	Latitude (degrees)	Longitude (degrees)	Elevation (m)	2003	2004
GPS Receivers					
Airdrie (AIRD)	51.28	–114.00	1081.5	X	X
Alford Lake (ALFD)	52.06	–115.09	1190.9		X
Brooks (BRKS)	50.57	–111.90	750.6	X	
Calgary (CALG)	51.08	–114.13	1116.9	X	X
Cochrane (COCH)	51.19	–114.47	1142.3	X	X
Cremona (CREM)	51.55	–114.49	1169.5	X	
Drumheller (DRUM)	51.46	–112.71	674.1	X	
Irricana (IRRI)	51.32	–113.61	920.9	X	
Limestone Mtn (LIME)	51.89	–115.37	1933.9		X
Mockingbird Lookout (MOCK)	51.43	–115.07	1905.4	X	
Olds (OLDS)	51.79	–114.09	1031.9	X	X
Strathmore (STRA)	51.06	–113.39	975.4	X	X
Sundre (SUND)	51.81	–114.64	1083.4	X	X
Sunshine (SUNS)	51.08	–115.78	2179.9		X
Three Hills (THIL)	51.71	–113.25	906.6	X	X
Vulcan (VULC)	50.41	–113.27	1046.8	X	
Radiosondes					
Airdrie Airport (AirdRS)	51.32	–113.88	1112.0	X	X
Olds-Didsbury Airport (OldsRS)	51.72	–114.12	1024.0	X	X
Sundre Airport (SundRS)	51.77	–114.68	1114.0	X	

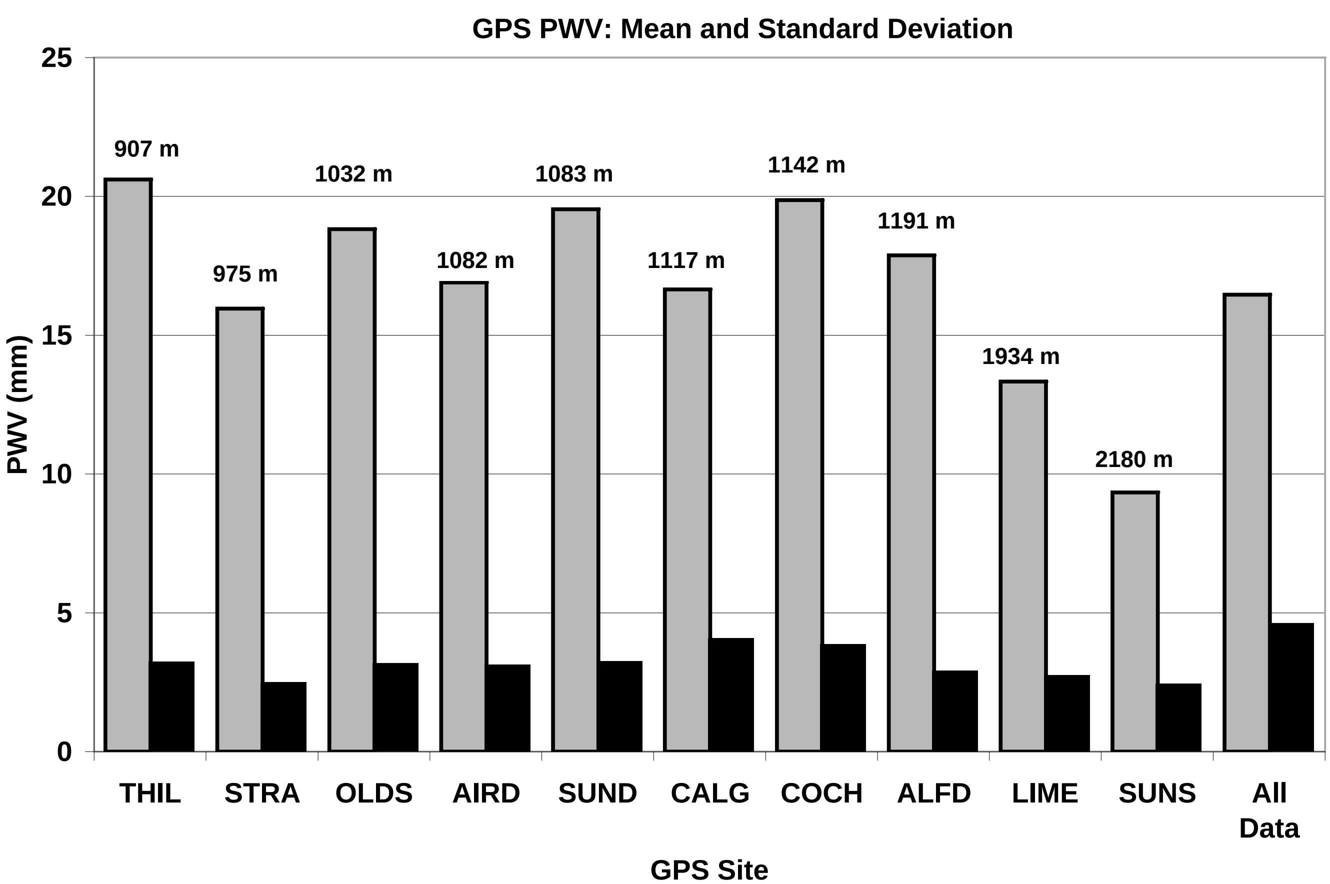


Fig. 2 GPS-derived PWV mean (grey) and standard deviation (black) values for 10 sites in the southern Alberta GPS network during A-GAME 2004. Orthometric height is noted above each site.

Radiosonde flights from AirdRS were typically initiated at 13:15, 17:15, 20:15 and 23:15 UTC during A-GAME 2003 and at 14:15, 17:15 and 23:15 UTC during A-GAME 2004. Some supplementary flights were released when conditions were favourable for the development of severe convective storms. Flights from OldsRS were usually initiated at 18:00 UTC with a second or third flight occurring in the late afternoon (between 21:00 and 23:00 UTC) if conditions for severe weather were favourable. Airsonde flights from SundRS (2003 only) were initiated at various times during the day (between 13:00 and 23:00 UTC) depending on severe weather precursors. During A-GAME 2003, a total of 32, 24 and 23 flights were released from AirdRS, OldsRS and SundRS, respectively. In 2004, 16 flights were released from AirdRS and 28 from OldsRS.

Quality analysis and control were performed manually via visual inspection of plotted temperature, humidity and wind data. Radiosonde flights with bad temperature or humidity data or those that terminated prematurely (before reaching 300 hPa) were eliminated from this analysis. Any remaining bad data were removed and replaced with a missing data flag prior to interpolation.

Radiosondes launched on or shortly after the hour take approximately 45 minutes to ascend through the boundary layer and lower troposphere and are time-stamped for the following hour (as is done in the operational network). A large proportion of the atmospheric moisture in the column is observed during the first 45 minutes. GPS PWV is derived from an average delay over the hour and time-stamped with the end time of the averaging period. Radiosonde PWV estimates are time-stamped with the hour after launch and compared directly to GPS PWV time stamped with the end of the averaging period. This means that a radiosonde launched at 17:15 UTC (time-stamped with 18:00 UTC) is compared with GPS PWV with the averaging period ending at 18:00 UTC. In this way, hourly GPS-derived PWV is matched as closely as possible in time with the radiosonde data.

A-GAME fieldwork was devoted, in large part, to establishing the accuracy of, or validating, PWV from GPS receivers in the SAN. It is difficult to carry out a thorough error analysis of PWV data derived from GPS techniques. For this reason, intercomparisons using universally accepted data are necessary; in this instance radiosonde data were used. The radiosonde data are assumed to provide the database standard. This is justified by other studies that show that most radiosonde errors (in pressure, temperature, humidity and winds) are systematic errors, usually resulting from either the manufacturer's calibration or user's pre-launch baseline errors (Strong, 1997). Thus, observed differences in PWV estimates between different co-released sondes provide an estimate of the maximum uncertainty. Strong (1997) determined the maximum uncertainty in this way to be less than ±0.5 mm, or ±1–3% depending on total vapour mass (nominally 15–40 mm), using Vaisala RS-80 and Airsonde AIR-3A sondes, the same sondes used during A-GAME.

The systematic dry bias of the RS-80 radiosondes is well documented (Barr and Betts, 1997; Fleming, 1998; Miloshevich et al., 2001; Turner et al., 2003). Lesht and Liljegren (1997), based on a comparison of radiosonde and microwave radiometer measurements of PWV, showed that the magnitude of the dry bias was strongly correlated with the instrument's date of manufacture. The physical explanation for this is related to sensor contamination from the radiosonde packaging. This, as well as other RS-80 calibration issues, is discussed in greater detail by Miloshevich et al. (2001). For RS-80 radiosondes manufactured prior to August 2002, Turner et al. (2003) suggest that a single correction factor can be used to correct the age-dependent dry bias. This correction factor for relative humidity is 0% when the radiosondes are new and increases to a maximum of 8% after one year (when the sensor contamination reaches an equilibrium). The authors show that this is equivalent to a PWV correction ranging from 2% for newer radiosondes to a maximum of approximately 12% for instruments older than one year.

The majority of the RS-80 radiosondes used in the 2003 and 2004 campaigns that were launched from OldsRS and AirdRS were manufactured in February 1998. A constant dry bias correction of 12% was applied to the observations made with these instruments. Some newer RS-80 radiosondes, manufactured after 2000, were used at OldsRS. No corrections were made to these observations. Also, no corrections were made to the Airsonde AIR-3A observations from SundRS.

d *GEM Model Data*

Gridded regional GEM NWP data were provided by the Canadian Meteorological Centre (CMC) for the period encompassing A-GAME 2004 (11–18 July). Note that the A-GAME 2003 period is not included in the GEM intercomparison because of a model change in May 2004 making the resolution inconsistent between the two A-GAME periods. The GEM data were provided in the same format available to the public at the time of the validation period. These data were used rather than the full resolution archived data in order to examine the accuracy of the information provided to other GPS and non-government researchers. Regional analysis (hour-0) data and hour-3, -6 and -9 prognoses were provided for both the 0:00 and 12:00 UTC model runs. Model parameters were available for 28 isobaric layers ranging from 1015 to 50 hPa and, for some parameters, the surface. The gridded model data were for a non-uniform 501 (longitude) × 399 (latitude) grid spanning most of North America with an approximate grid spacing of 15 km. Complete model and parameter details for this gridded data set are publicly available on the CMC website (http://www.weatheroffice.gc.ca/grib/index_e.html).

To derive PWV above each GPS site from GEM, height, pressure, temperature and specific humidity fields were linearly interpolated horizontally to the site location. Due to differences between the GEM topography and actual GPS site heights, model surface pressure was interpolated or extrapolated to the height of the GPS site as described in Deblonde et al. (2005). The difference between the orthometric height of the southern Alberta GPS sites and the model topography

(ΔZ, defined as GPS elevation minus GEM elevation) ranged from –97 m at Cochrane to 325 m at Limestone Mountain and are summarized, along with the intercomparison results, in Table 4. GEM-derived PWV estimates were produced by integrating through the specific humidity fields.

The GEM output is considered to be valid at the moment it is time-stamped (i.e., there is no temporal averaging and it is valid at time t, but the GPS PWV is considered to be a batch estimate of 30-second observations over the previous hour (time t-1 to time t). Therefore, a direct comparison between the 1-hour GPS estimate and the instantaneous GEM output may not be appropriate. Rather, the 1-hour GPS PWV estimates are averaged for GEM time t and GEM time t+1 for comparison with GEM PWV.

3 Results

a *GPS versus Radiosondes*

The intercomparison statistics for GPS and nearby radiosonde sites at AirdRS, OldsRS and SundRS are summarized in Table 2. For the 2003 study period, GPS data from Calgary are substituted for missing GPS data for Airdrie (Table 2 also includes statistics for each individual site) comprising 50% of the 2003 Airdrie observations. The overlap of the two GPS sites had an r^2 value of 0.94 which strengthens the argument for combining the two sites for comparison with AirdRS. The scatter plots for both the 2003 and 2004 intercomparisons are shown in Fig. 3 (for AirdRS in 2003, the Calgary and Airdrie data are marked with black and grey circles, respectively) and the time-trend intercomparisons are shown in Fig. 4.

Correlation coefficients (r^2) varied from 0.76 (Airdrie/Calgary-2003) to 0.84 (Olds- and Sundre-2003) and generally increased from 2003 to 2004. All correlations are significant at $p < 0.0005$. The average r^2 for all sites (using the combined Airdrie/Calgary data in 2003) was 0.81. The bias (defined as GPS-derived PWV minus radiosonde-derived PWV) ranged from 1.4 (GPS wet bias at Olds in 2004) to –1.7 (GPS dry bias at Airdrie/Calgary in 2003). From 2003 to 2004, there were decreases in the magnitude of the bias at both OldsRS and AirdRS. Overall, the average bias was -0.6 mm indicating that the GPS estimates of PWV were slightly drier than those derived from radiosondes. The SD was used as an indicator of the variability in the bias and ranged from 1.2 mm (Olds-2003) to 2.3 mm (Olds-2004). The SD remained relatively constant from 2003 to 2004 at Airdrie. Overall, the average SD was 1.6 mm.

The qualitative time trend analysis of the GPS and radiosonde PWV observations (shown in Fig. 4) suggests that the GPS and radiosonde trends in PWV are very similar in both 2003 and 2004. The GPS dry bias in 2003 can be seen in Figs 4a, 4b and 4c where many of the radiosonde-derived values of PWV are higher (wetter) than the corresponding GPS-derived values. The apparent GPS wet bias at Olds in 2004 can be seen in Fig. 4e. There is very close agreement between the Calgary and Airdrie GPS-derived PWV during periods of overlap in both 2003 (Fig. 4a) and 2004 (Fig. 4d). It should be noted that the Sundre GPS-derived PWV is included in the Olds time series (Figs 4b and 4e) for two reasons: 1) in 2003, the Sundre data fill in missing Olds GPS data so that we can still see the evolution of PWV with time, and 2) there were no radiosondes released from Sundre in 2004 so the time series shows that the Sundre GPS is tracking well with both the Olds GPS and OldsRS. The Olds and Sundre GPS PWV time series are very similar, with Sundre often wetter than Olds.

b *GEM versus GPS*

The period of intercomparison for the GPS-derived and GEM-modelled PWV were days 193 to 200 during A-GAME 2004. In this analysis and discussion, we used the GPS-derived PWV as the truth for the purpose of model verification. Figure 5 shows the intercomparison of all of the GEM-modelled PWV data with the GPS-derived data for all 10 sites combined with the intercomparison statistics summarized in Table 3 (broken down by prognosis time and storm occurrence) and Table 4 (broken down by site). For reference, site information can be found in Table 1. Bias is calculated as GEM-modelled minus GPS-derived PWV.

On average, GEM overestimates PWV during the study period by 0.5 mm with an SD of 2.9 mm. There may be some bias dependency on the total PWV where GEM tends to have a wet bias at low PWV (Figs 5 and 6). However, the degree of scatter inhibits any trend analysis.

Differences between GPS-derived and GEM-modelled PWV were examined based on analysis (hour-0) and prognosis (hour-3, -6 and -9) times and are shown in Fig. 6 and Table 3. The GEM wet bias is lowest at hour-0 (0.2 mm) and increases to a maximum at hour-9 (0.9 mm). Following this, the SD was lowest at hour-0 and -3 (2.5 mm) and increased to a maximum (3.2 mm) at hour-9. The correlations reflected this pattern with a higher r^2 at hour-0 and -3 (0.71), decreasing to a minimum at hour-9 (0.52). These patterns are visually

TABLE 2. Summary of GPS- and radiosonde-derived PWV intercomparison statistics.

Year	Radiosonde/GPS	r^2	Bias (mm)*	SD (mm)	n
2003	AirdRS/Airdrie	0.64	–1.8	1.6	12
	AirdRS/Calgary	0.74	–1.9	1.7	24
	AirdRS/Airdrie-Calgary	0.76	–1.7	1.6	24
	OldsRS/Olds	0.84	–0.9	1.2	17
	SundRS/Sundre	0.84	–1.0	1.4	14
2004	AirdRS/Airdrie	0.82	–0.6	1.4	14
	OldsRS/Olds	0.81	1.4	2.3	10

*Bias = GPS - Radiosonde

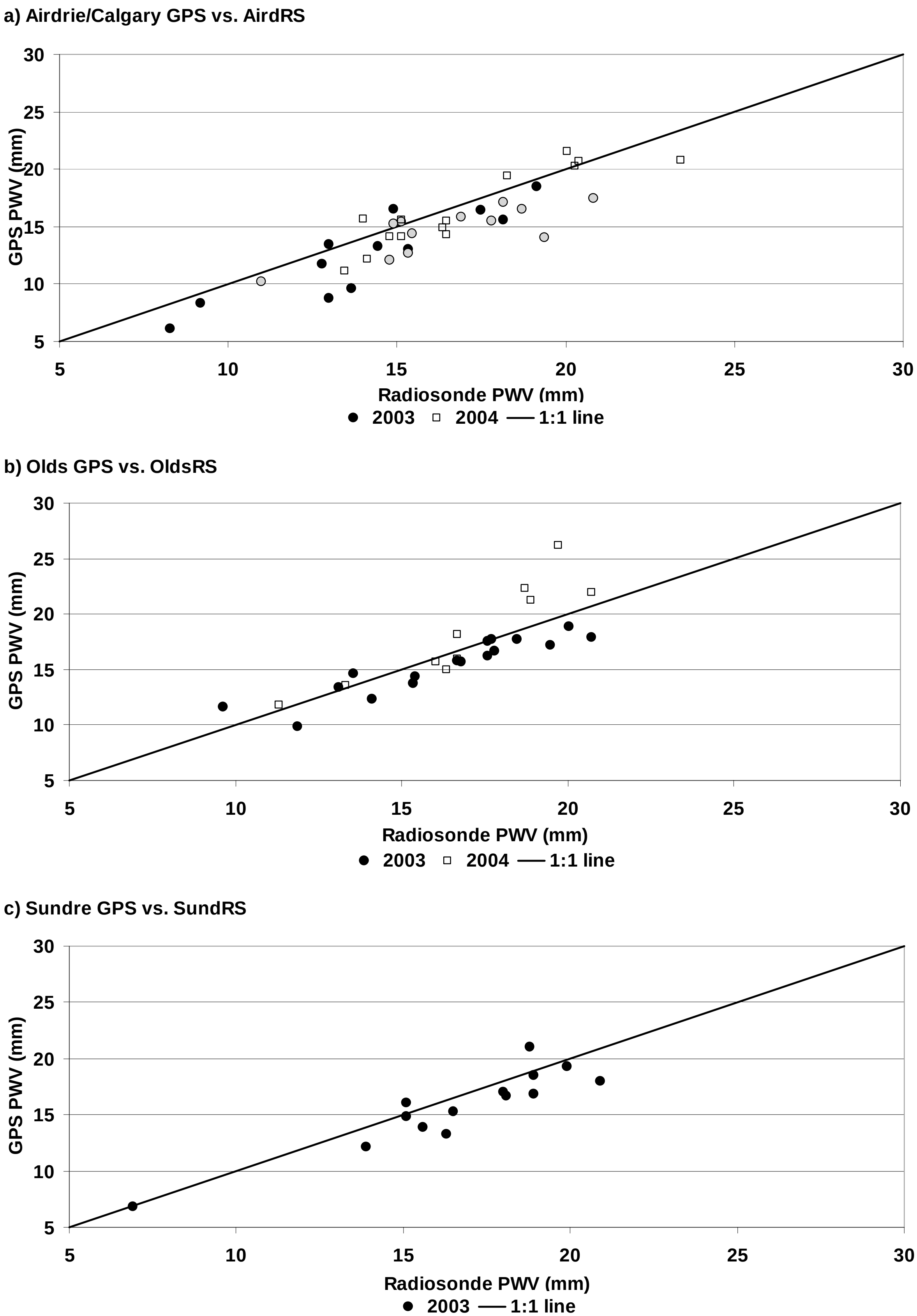


Fig. 3 Intercomparisons of radiosonde- and GPS-derived PWV at nearby sites in the southern Alberta GPS network during A-GAME 2003 and 2004 for a) Airdrie/Calgary (AirdRS; 2003 Calgary in black circles and 2003 Airdrie in grey circles), b) Olds (OldsRS) and c) Sundre (SundRS).

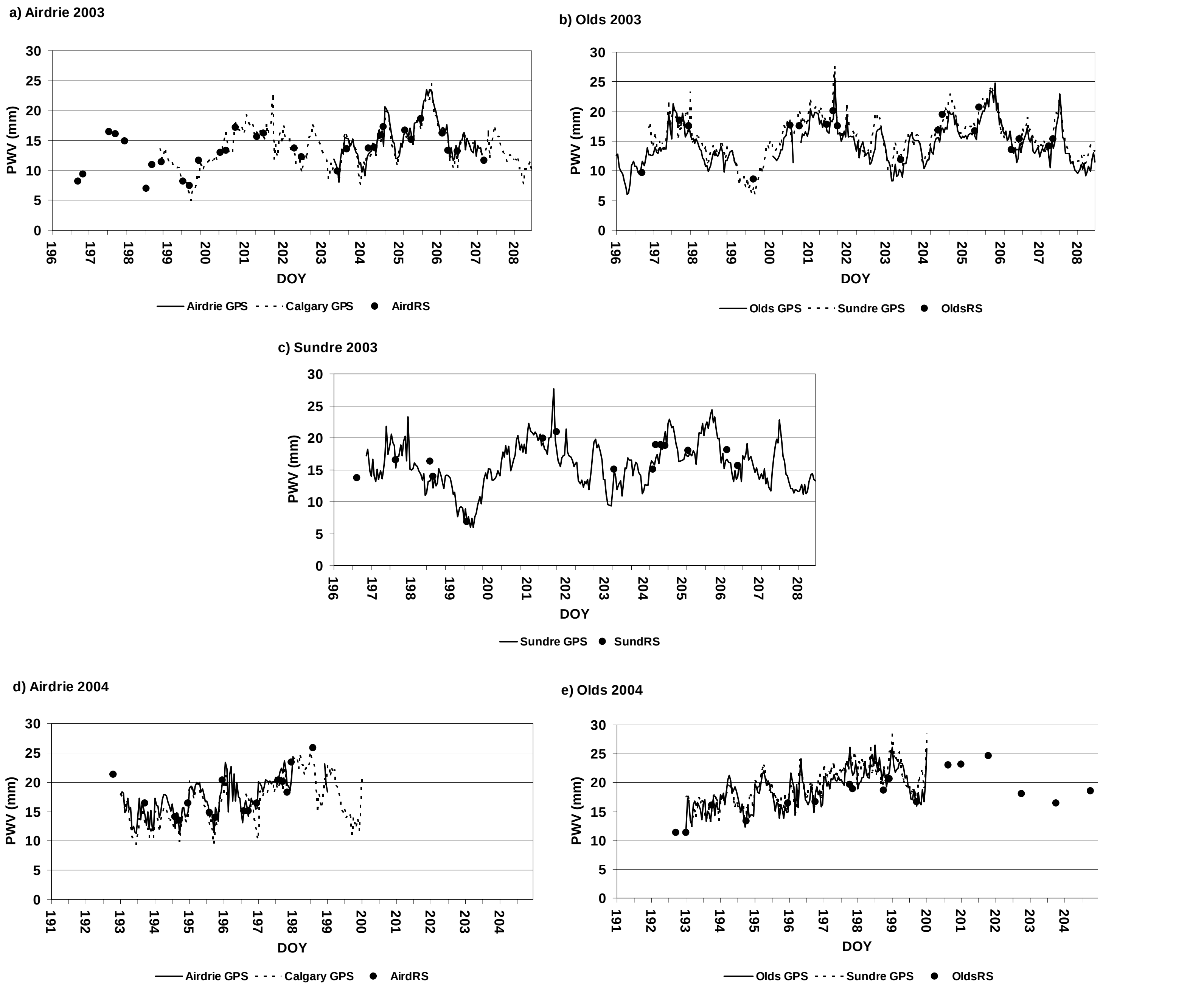


Fig. 4 Time series showing the similarities between the radiosonde- and GPS-derived PWV at nearby sites in the southern Alberta GPS network during A-GAME 2003 and 2004 for a) Airdrie-2003, b) Olds-2003, c) Sundre-2003, d) Airdrie-2004 and e) Olds-2004.

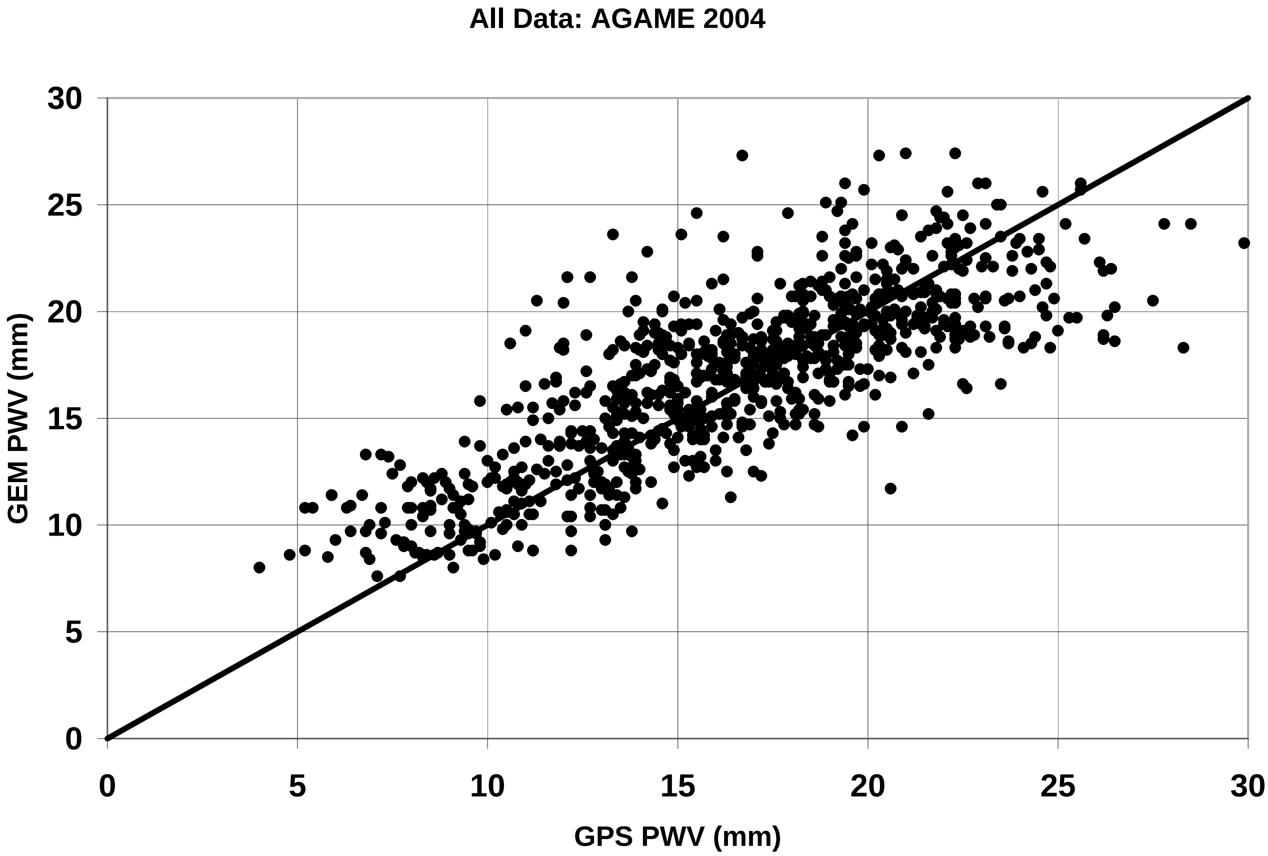


Fig. 5 Intercomparison of GPS- and GEM-derived PWV for all 10 sites in the southern Alberta GPS network during A-GAME 2004.

TABLE 3. Intercomparison of GPS and GEM PWV for the A-GAME 2004 data set. Results are presented for analysis (hour-0) and prognosis times (hour-3, -6 and -9) as well as storm and non-storm periods during the campaign.

	Analysis or Prognosis Time	Mean GPS PWV (mm)	PWV Difference GEM/GPS Mean (mm)	PWV Difference GEM/GPS SD (mm)	(GEM-GPS) Correlation r^2	n
	All	16.5	0.5	2.9	0.63	870
All Data	0	16.5	0.2	2.5	0.71	209
	3	16.5	0.4	2.5	0.71	224
	6	16.3	0.5	3.0	0.59	219
	9	16.6	0.9	3.2	0.52	218
	Storm	17.7	0.1	3.5	0.53	286
	Non-Storm	15.7	0.3	2.1	0.75	462
Non-Storm	0	15.6	0.3	2.0	0.77	119
	3	15.6	0.2	2.0	0.79	122
	6	15.4	0.5	2.5	0.69	107
	9	16.1	0.1	2.0	0.74	114
Storm	0	18.7	–0.5	3.5	0.59	66
	3	17.3	0.1	3.2	0.59	68
	6	17.1	–0.5	3.3	0.53	80
	9	17.6	1.1	3.9	0.46	72

apparent in Fig. 6; it shows increasing scatter from hour-0 (Fig. 6a) and hour-3 (Fig. 6b) to hour-9 (Fig. 6d).

Intercomparison results from individual sites (Table 4) show that the mean bias varies from 1.9 mm (GEM wet bias) to -1.4 mm (GEM dry bias) and the SD ranges from 2.1 mm to 4.1 mm. Figure 7a shows the relationship between site elevation and bias (circles) and SD (triangles) and suggests no significant trend in either. Similarly, Fig. 7b shows the relationship between bias and SD with ΔZ (listed in Table 4). Again, no correlation is apparent. This indicates that the

TABLE 4. Summary of GPS and GEM PWV intercomparisons for all SAN sites during A-GAME 2004.

	ΔZ (m)	Mean PWV (GPS) (mm)	PWV Bias (GEM-GPS) Mean (mm)	PWV Bias (GEM-GPS) Standard Deviation (mm)	GEM/GPS Correlation r^2	n
Three Hills	52.2	20.6	–1.4	2.7	0.32	32
Strathmore	49.2	16.0	1.9	2.7	0.12	25
Olds	37.1	18.8	0.3	2.6	0.36	111
Airdrie	–1.3	16.9	0.8	3.1	0.21	97
Sundre	–52.6	19.5	–0.4	2.7	0.41	111
Calgary	-0.7	16.7	1.3	3.2	0.45	104
Cochrane	–97.2	19.9	–0.1	4.1	0.15	57
Alford Lake	–59.0	17.9	0.9	2.5	0.39	111
Limestone	325.5	13.3	–0.3	2.3	0.36	111
Sunshine	184.3	9.3	1.4	2.1	0.28	111

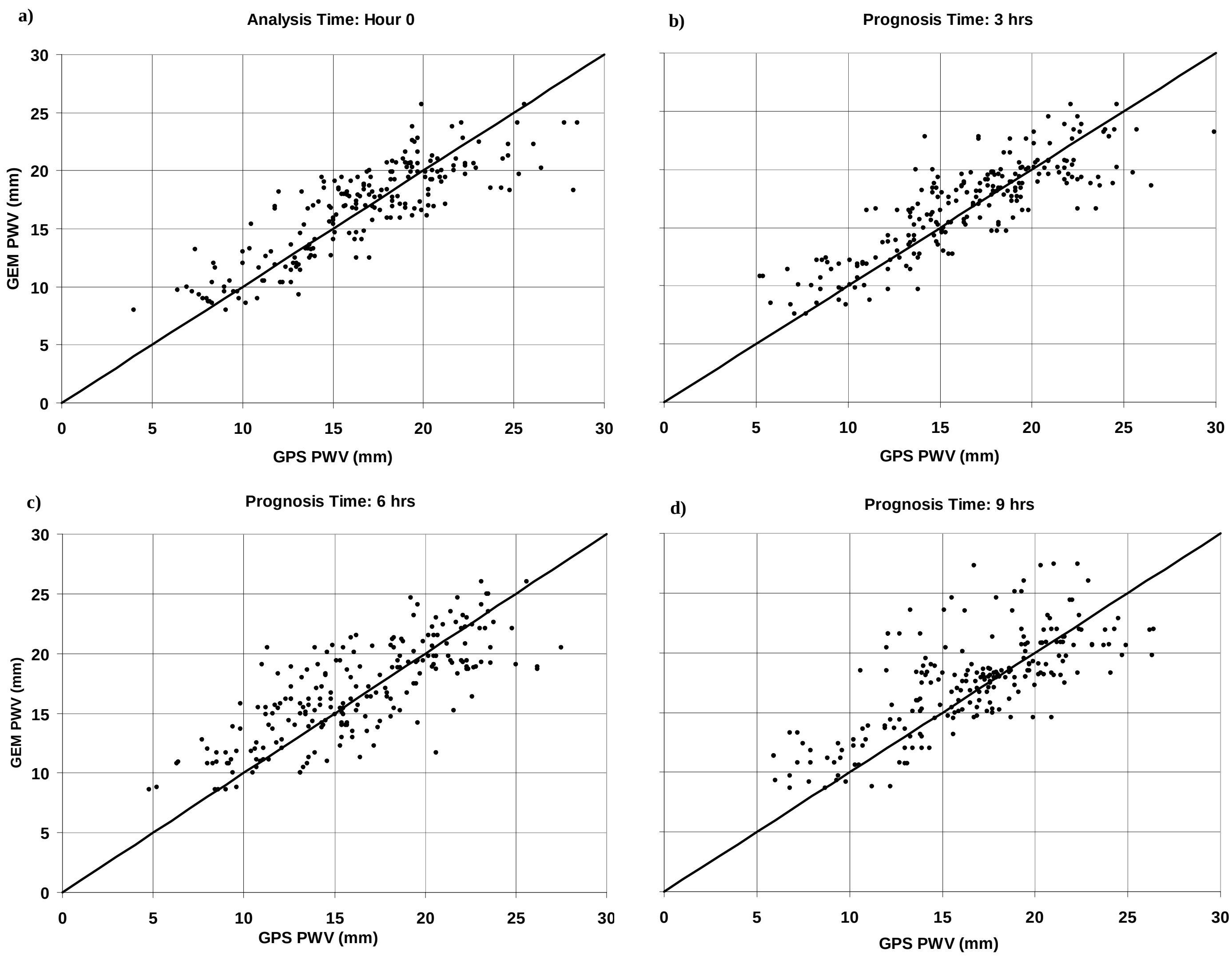
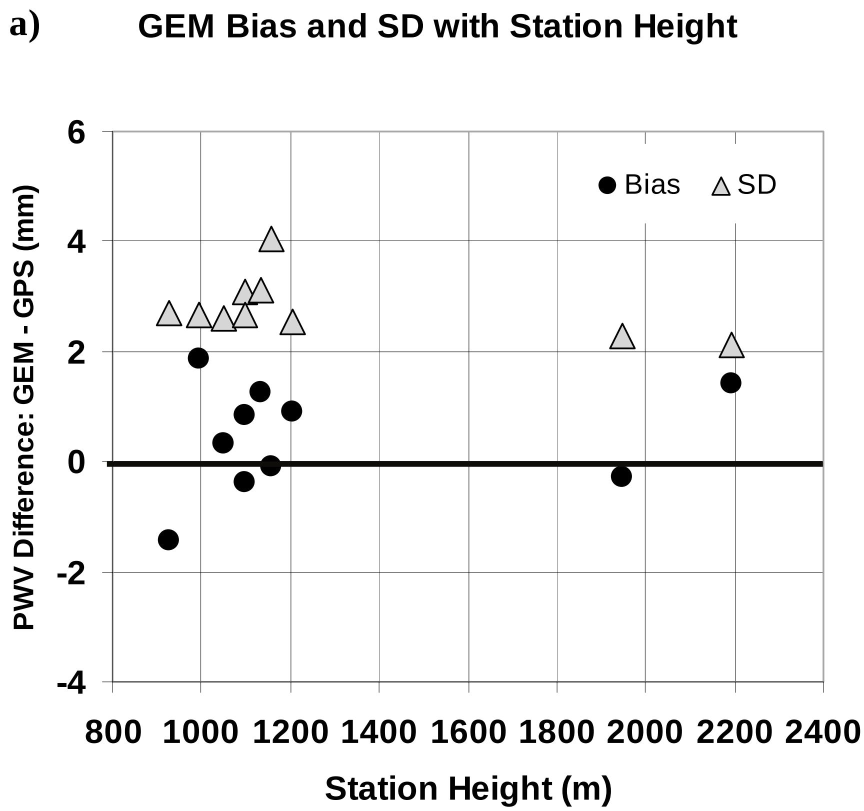


Fig. 6 Intercomparison of GPS and GEM PWV for a) analysis time (0-hour), b) 3-hour, c) 6-hour and d) 9-hour prognosis times.

model is functioning consistently with elevation and that no bias was introduced as a result of the vertical interpolation or extrapolation. Further analysis showed a spatial correlation in SD with higher values found in the southwest corner of the network, east of the Rocky Mountain foothills (Cochrane, Calgary and Airdrie).



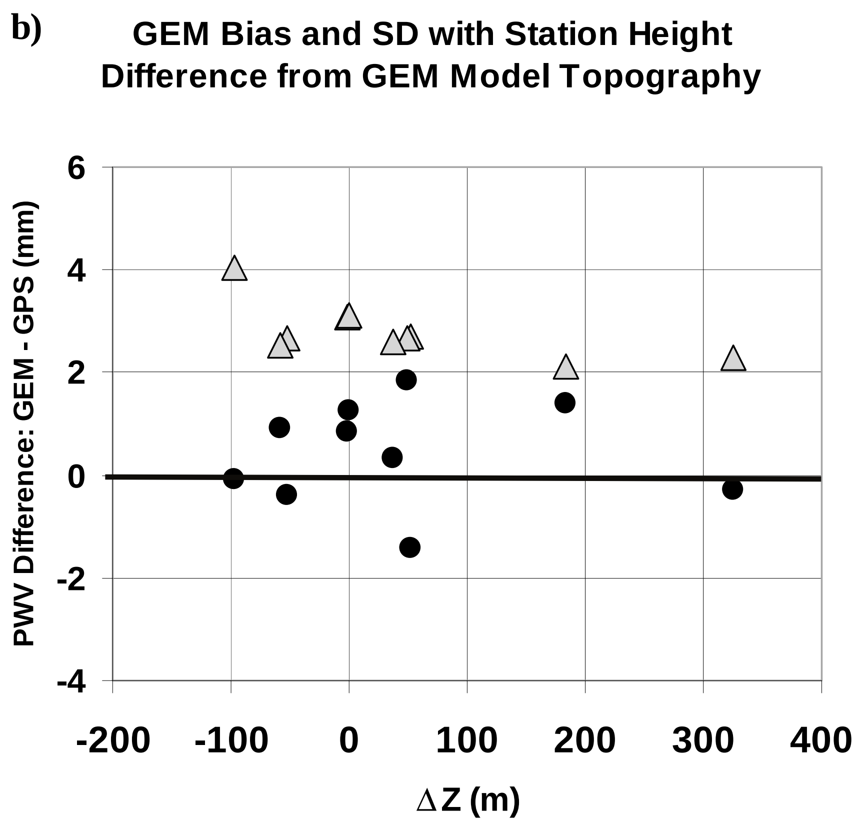


Fig. 7 Mean PWV bias (GEM-GPS) (black circles) and standard deviation (grey triangles) as a function of a) orthometric GPS site height and b) the difference between orthometric GPS site height and GEM model topography height.

GEM-modelled PWV performance was evaluated based on the presence or absence of a storm within the network. For this analysis, a storm event was somewhat qualitatively identified using radar images obtained from the Olds-Didsbury airport (OldsRS) for a subset of days available during the A-GAME 2004 campaign (day 193 to 199). Figure 8 shows the time evolution of the GEM bias and the four storm events during that period are indicated as shaded areas. Alberta storm occurrences typically exhibit a diurnal peak in activity during the evening (18:00 local time, 00:00 UTC) and lulls in the early morning (06:00 local time, 12:00 UTC) and the distribution of A-GAME storm events fits this pattern (Fig. 9a). Storm events and non-storm periods occur with similar frequency during the analysis and prognosis times (Fig. 9b) and therefore, model output time should not bias the results. GPS-derived PWV ranged from 4.0 mm to 24.6 mm during non-storm periods which increased during storm events to a range from 6.3 mm to 29.9 mm (Fig. 9c). Mean GPS-derived PWV increased from 15.7 mm during non-storm periods to 17.7 mm during storm events. Intercomparison statistics are listed in Table 3.

The effect of storm events on the GEM bias was small and exhibited a small decrease from non-storm periods. Of greater consequence, the SD increased from 2.1 mm during non-storm periods to 3.5 mm during storm events. Reflecting this, the correlation decreased from 0.75 to 0.53 for non-storm and storm periods respectively. These intercomparisons are shown in Fig. 10. The results imply that the storm PWV is not as accurately modelled by GEM over the region and this has implications for using GEM-derived PWV forecasts for severe weather (and other atmospheric) research.

4 Discussion

Differences between radiosonde-derived and GPS-derived PWV values are typically within the ranges reported by others although the correlation coefficients in this study are somewhat lower. Deblonde et al. (2005) reported average r^2 values of 0.94 while Yang et al. (1999) reported a range from 0.88 to 0.94. Lower coefficients of 0.76 to 0.84 during A-GAME can largely be attributed to a combination of a small data set observed during periods of high spatial and temporal variability in PWV. More encouraging are the SD statistics which were typically lower during A-GAME (1.2 to 2.3 mm) than those reported during other intercomparisons (e.g., Köpken, 2001; Deblonde et al., 2005). Furthermore, the agreement between radiosonde-derived and GPS-derived PWV has to be considered very good considering that the two techniques derive PWV in very different ways. Many factors could contribute to the differences seen in the intercomparison. These include, but are not limited to, the positions of the GPS satellites (and therefore signal paths) relative to the ascent pathway of the radiosonde, the time differential between the GPS integrations and the radiosonde measurements, varying distance between the GPS receiver and radiosonde launch sites, GPS signal multipath, and radiosonde error and bias. Most of these are difficult to quantify.

The humidity bias issue with the Vaisala RS-80 radiosondes (discussed in Section 2c) may not be completely resolved. An overcorrection of the dry bias in the RS-80 radiosondes used at AirdRS and OldsRS in 2003 and at AirdRS in 2004 could explain much of the apparent GPS dry bias. However, some independent tests by the authors using dual Vaisala RS-80/RS-92 radiosonde packages (where the RS-92 is not subject to the same contamination issue as the RS-80) suggests that the 12% bias adjustment is appropriate and possibly even too low. At OldsRS in 2004, newer (post-2000) RS-80 radiosondes were used more frequently and therefore the majority of the data were not adjusted. Although Vaisala states that the contamination problem was remedied by using inert sensor packaging, the effect on the dry bias has not been thoroughly examined (Turner et al., 2003). An under-correction at OldsRS in 2004 could explain the GPS wet bias. The Airsonde system, such as the one used at SundRS, has historically shown a wet bias in humidity measurements (Strong et al., 1996), although it is not certain just how much of this Airsonde wet bias was due to the Vaisala RS-80 dry bias during radiosonde intercomparisons.

Other discrepancies between radiosonde- and GPS-derived PWV could result from differences in the atmospheric column measured by each system. The radiosonde estimate is really integrated slantwise rather than vertically, in the direction taken by the ascending instrument due to the upper wind field, predominantly an eastward component in most instances. Moreover, these upper winds can carry a radiosonde 10 to 20 km from its release point by the time the radiosonde reaches the top of the boundary layer (i.e., 400 hPa). GPS PWV estimates are also derived through a slantwise integration but the signal paths are dependent on which satellites are in view during the observation period (but usually towards the southern horizon) and totally independent of the wind field. Azimuthal symmetry is assumed when processing the GPS PWV observations thereby averaging through gradients in the surrounding atmosphere that the radiosonde might pass through during its ascent.

Another potential source of discrepancy between GPS-derived and radiosonde-derived PWV could be the difference in elevation between the radiosonde and GPS measurement sites. AirdRS and SundRS were both 31 m higher than their neighbouring GPS sites while OldsRS was 8 m lower (Table 1). Observations made from a higher elevation could mean a lower observed PWV (and vice versa) and a resulting radiosonde adjustment would increase the GPS dry bias at Airdrie and Sundre and increase the wet bias at Olds. The total adjustment would be small, on the order of 1–3% for AirdRS and SundRS (and even smaller for OldsRS). Since the adjustment would be hypothetical, and considering the relative close proximity of the GPS and radiosonde observations, it was not made prior to analysis.

Differences between GEM model output of PWV and GPS estimates are expected because of the way in which they are derived. GEM data are assimilated and integrated in time and space to provide a 'snapshot' of the state of the atmosphere in

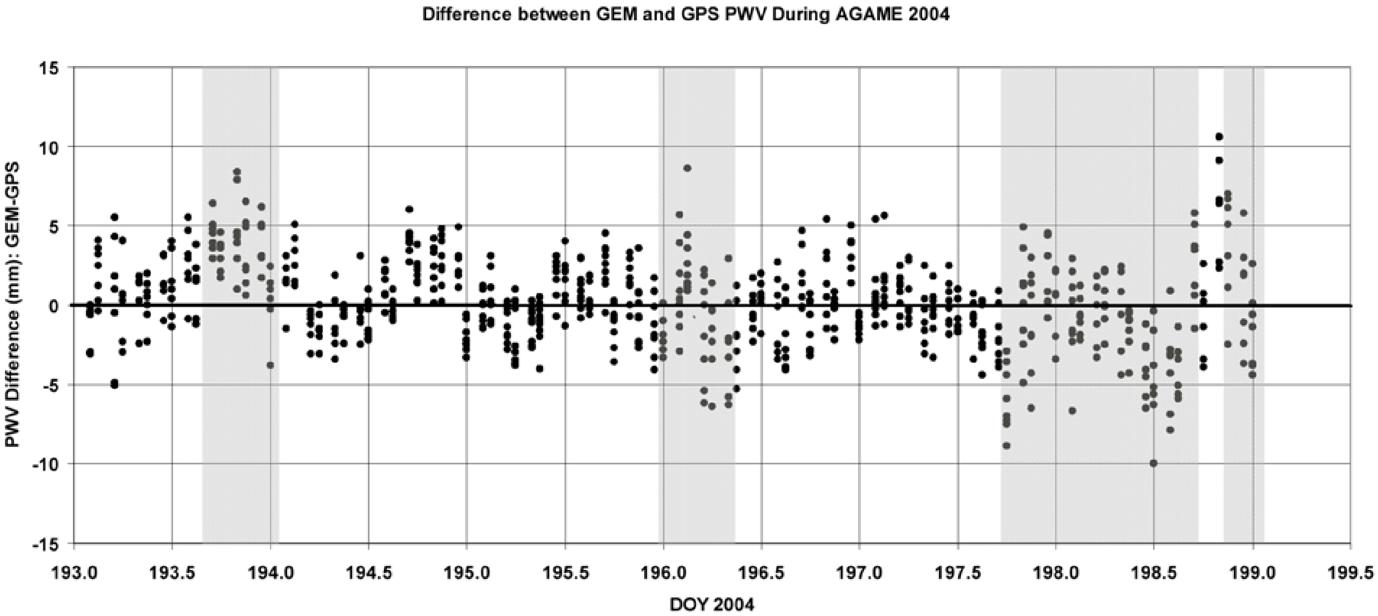


Fig. 8 Time series of the difference between GEM- and GPS-derived PWV for all sites over days 193–199 in 2004. Areas shaded in grey indicate periods of storm activity within the GPS network.

a grid cell (or column of grid cells) at a specific instant in time, whereas a radiosonde observation, for example, is integrated over a longer period as the instrument ascends. The GEM grid spacing limits the model resolution and therefore cannot reproduce fine-scale variability that might be detected by a more closely spaced GPS network. Thus, point comparisons in space and time between these three methods can be expected to produce wide scatter in some instances, especially during convective weather.

The strong correlations and relatively low bias estimates between GPS- and radiosonde-derived PWV and the qualitative agreement in the temporal trends of regional PWV (Fig. 4, Table 2) indicate a potential for application of high resolution GPS-derived PWV to meteorological research and forecasting in the southern Alberta region. It has been demonstrated that regional estimates of GPS-derived PWV using the SAN are useful in examining the pre-storm environment for severe weather (Hill, 2006) as well as the dynamics of regional atmospheric moisture as storms propagate within the network (Hoyle, 2005). The evolving capability of near real-time signal processing techniques will increase the reliability of GPS networks for severe weather forecasting.

The southern Alberta Network of GPS receivers is unique in Canada and offers opportunities to examine dynamics in atmospheric moisture in this region of complex topography. However, limitations in the spatial distribution and temporal availability of the GPS estimates of PWV make alternative sources of data, such as GEM NWP output, necessary. In turn, the relatively high correlations and low bias estimates between radiosonde and nearby GPS measurements indicate that GPS-derived PWV can be used to estimate the dynamic bias in GEM analysis and prognosis output.

The comparison between GPS-derived and GEM-modelled PWV shows that the model successfully characterizes the PWV field within the GPS network at the time of initialization (hour-0) and continues this through the hour-3 prognosis. These high correlations are somewhat surprising given that the model is initialized using atmospheric moisture information derived from radiosondes that are not likely representative of southern Alberta. The radiosonde site closest to the network is located at Stony Plain which is more than 170 km north of the closest GPS site. The radiosonde site directly upstream is located in Kelowna, which is nearly 300 km across complex topography from the nearest GPS site on the west side of the network. Not surprisingly, the GEM prognosis of PWV begins to deviate more from the GPS-derived PWV after the hour-3 prognosis. Researchers using these data for atmospheric moisture budgets (or other atmospheric processes research) and severe weather forecasters need to recognize this increasing bias and variability with increasing prognosis length.

The results of the intercomparison of GEM-modelled and GPS-derived PWV detailed in this paper are in contrast with the results from global GEM intercomparisons reported by Deblonde et al. (2005); our results indicate that the GEM model produced consistently wetter PWV values than the GPS-derived values. Our results do agree with the findings of Deblonde et al. (2005) showing that GEM-modelled PWV becomes wetter with increasing prognosis time. The SDs of the GPS-derived and GEM-modelled PWV are consistent with the findings of Deblonde et al. (2005), with both analyses showing an increase in the SD from the analysis to the prognosis outputs.

The results of the storm event versus the non-storm period comparison were as expected. The correlation between the

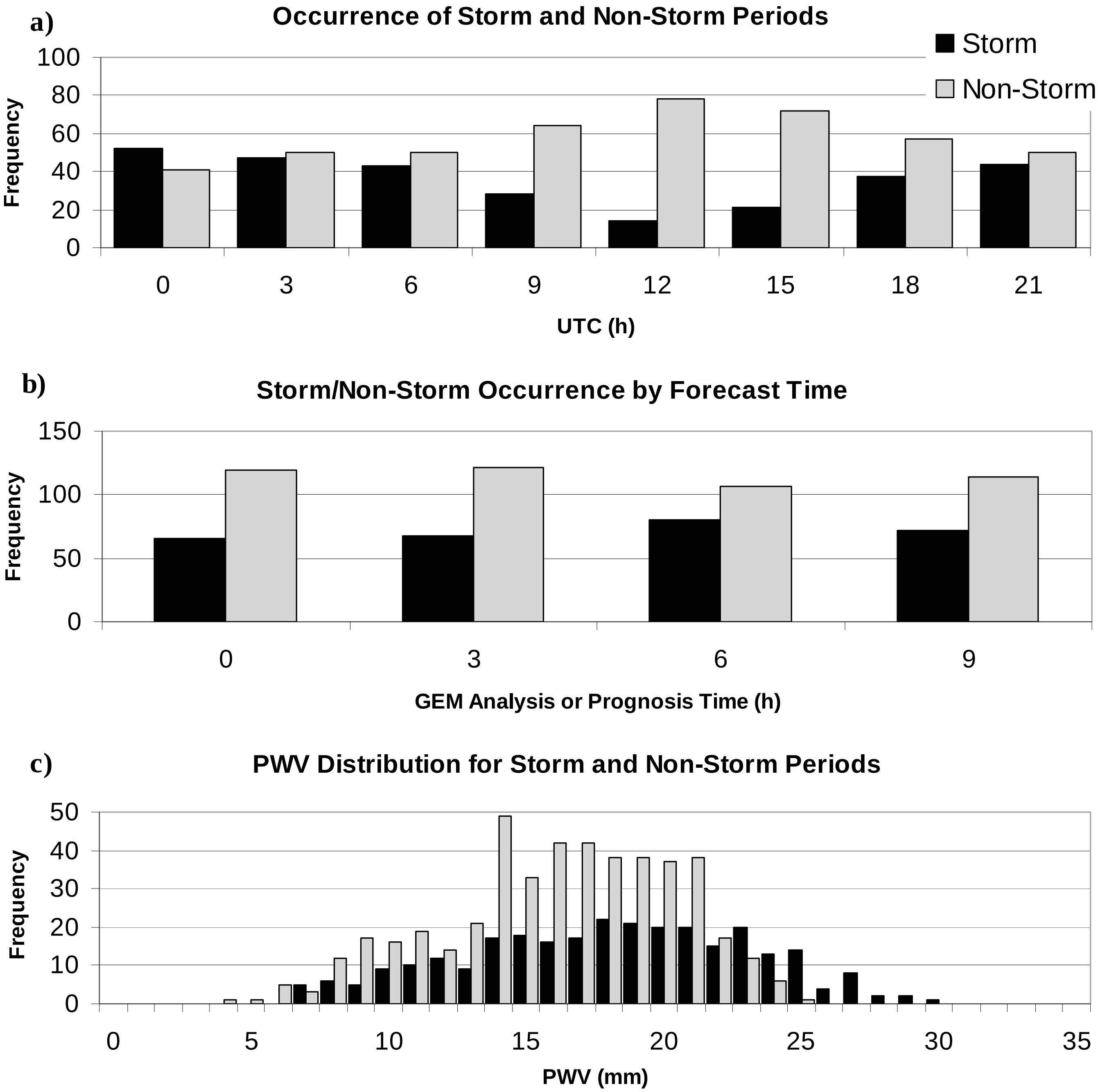


Fig. 9 a) Number of hourly occurrences of storm and non-storm events during A-GAME 2004; b) Hourly occurrences of storm and non-storm periods during analysis (hour-0) and prognosis times (hour-3, -6, -9); c) Distribution of GPS PWV from storm and non-storm events during A-GAME 2004.

GPS-derived and GEM-modelled PWV decreases substantially when a significant storm propagates through the network. Even though the overall magnitude of the bias between GPS-derived and GEM-modelled PWV is lower for storm events, the lower correlations and higher variability suggest that the GEM model does not accurately resolve the rapidly evolving atmospheric moisture fields during such events in the southern Alberta region. Given the analysis described in Section 3b that indicates an increase in variability with prognosis time, we speculate that the decrease in GEM model performance during storm events could be due to a higher proportion of hour-6 and hour-9 prognosis data in the analysis (i.e., storms occur more frequently during GEM hour-6 and hour-9 when the bias and SD are higher rather than during hour-0 and hour-3). Although the storm event analysis does have a higher proportion of hour-6 and hour-9 prognosis data (Fig. 9b), the difference (with respect to non-storm periods) is only 5% which is believed to be negligible. The significance of these results resides in the fact that atmospheric researchers are often most interested in the model moisture fields shortly

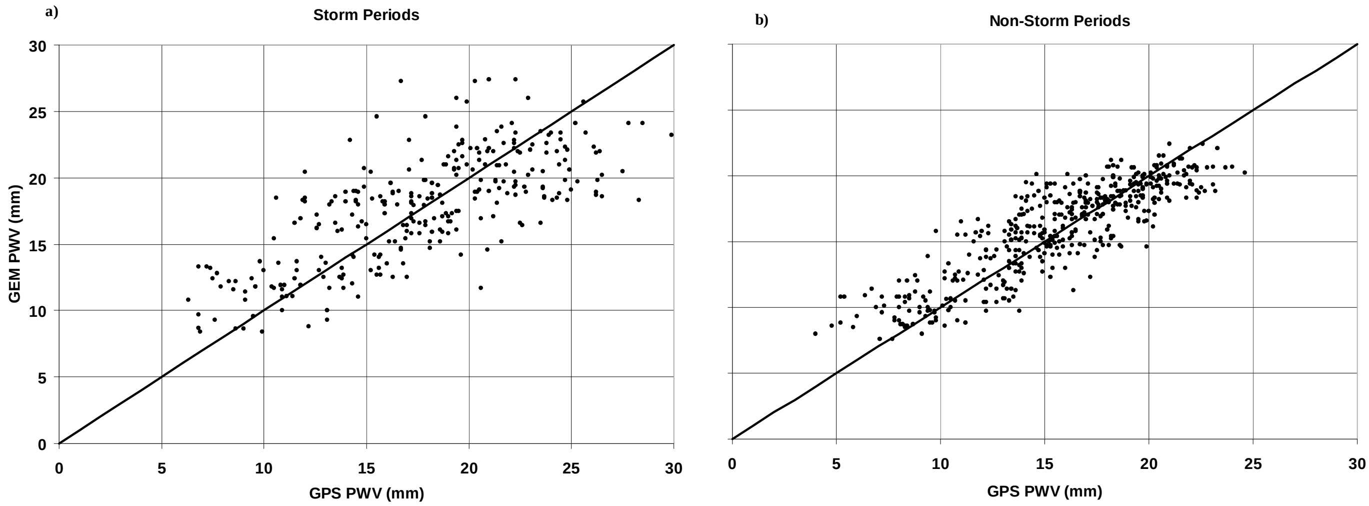


Fig. 10 Intercomparison of GEM and GPS PWV for a) storm and b) non-storm periods during A-GAME 2004.

before or during storm events but it is obvious that caution is required when using GEM-modelled PWV during significant disturbances in southern Alberta.

An encouraging result of the GPS versus GEM comparison is the absence of decreasing reliability in the model with increasing elevation. There is no apparent trend in either the GEM bias or the SD with increasing elevation. This suggests two possibilities: 1) the GEM model adequately resolves the PWV fields regardless of the complex topography, and/or 2) the interpolation of the GEM-modelled PWV data for ΔZ was done correctly and effectively.

The results from the site PWV comparisons showed that there may be a geographical effect on the SD in the region spanned by the network. The SD decreased with distance from the southwest corner of the network, on the east side of the Foothills (i.e., at Cochrane). The increased scatter for the sites closest to Cochrane may be due to the nature of the GEM model accuracy in that region or could also be attributed to the variability of the storms in that region. Further investigation with a longer data set would be beneficial in providing insight into this apparent effect.

5 Conclusions

The ability to use GPS techniques to retrieve PWV has been proven often but the variation in bias and SD among intercomparisons (and even between sites in the same intercomparison) suggests that the exercise is still worthwhile. By 'benchmarking' GPS-derived PWV with conventional radiosonde measurements in southern Alberta, any inherent bias and the variability in this bias can be assessed. This study has shown that the GPS receivers in the SAN that were close to the radiosonde launch sites showed a general dry bias that averaged 0.6 mm with an average SD of 1.6 mm. Regardless of the radiosonde issues, the reported intercomparison statistics are all within the ranges shown by previous intercomparisons and suggest good performance from the GPS techniques during A-GAME. This is not only encouraging for the continued use of these network data for atmospheric science but also provides confidence in using these data to examine the performance of GEM NWP atmospheric moisture products in this region.

The performance of the GEM model in resolving PWV in southern Alberta, compared to GPS-derived PWV, was very favourable. Overall, there was a wet bias in the GEM output of 0.5 mm which tended to increase with increasing prognosis time. The GEM correlation with GPS was high for the hour-0 analysis and hour-3 prognosis outputs (0.71) and dropped with later prognoses (0.52 at hour-9). This was also reflected in the SD which varied from 2.5 mm at hour-0 to 3.2 mm at hour-9. We also found that the model performance was reduced during storm activity in the region, likely due to rapid evolution of regional PWV that is difficult to resolve. Although there was significant variability in the model performance from location to location, we found no significant relationship between model performance and elevation.

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