JSHESS early online view

Using GNSS Data for Real-time Moisture Analysis and Forecasting over the Australian Region I. The System

John Le Marshall[1], Robert Norman[2], David Howard[1], Susan Rennie[1], Michael Moore[3], Jan Kaplon[4], Yi Xiao[1], Kefei Zhang[2], Carl Wang[3], Ara Cate[2], Paul Lehmann[1], Xiaoming Wang[2], Peter Steinle[1], Chris Tingwell, Tan Le[1], Witold Rohm[4] and Diandong Ren[1]

[1] Bureau of Meteorology, Victoria, Australia
[2] RMIT University, Victoria, Australia
[3] Geoscience Australia, Canberra, Australia
[4] Wroclaw University of Environmental and
Life Sciences, Poland

(Manuscript received December 2018; accepted July 2019)

The use of high spatial and temporal resolution data assimilation and forecasting around Australia's capital cities and rural land provides an opportunity to improve moisture analysis and forecasting. To support this endeavour, RMIT University and Geoscience Australia have worked with the Bureau of Meteorology (BoM) to provide real-time GNSS (Global Navigation Satellite System) Zenith Total Delay (ZTD) data over the Australian region, from which a high-resolution total water vapour field for SE Australia can be determined. The ZTD data can play an important role in high-resolution data assimilation by providing mesoscale moisture data coverage from existing GNSS surface stations over significant areas of the Australian continent. The data are now used by the BoM's high-resolution ACCESS-C3 capital city NWP systems, the ACCESS-G3 Global system and have been used by the ACCESS-R2-Regional NWP model. A description of the data collection and analysis system is provided. An example of the application of these local GNSS data for a heavy rainfall event over SE Australia/Victoria is shown using the 1.5km resolution ACCESS-C3 model, which is being prepared for operational use. The results from the test have been assessed qualitatively/synoptically and also have been examined quantitatively using the Fractions Skills Score which shows the reasonableness of the forecasts and demonstrates the potential for improving rainfall forecasts over south-eastern Australia by the inclusion of ZTD data in constructing the moisture field. These data have now been accepted for operational use in NWP.

1   Introduction

Atmospheric water vapour is highly variable in time and space and its determination is a vital component of accurate, high-resolution analysis. It is also important in terms of forecast accuracy. A dearth of high-resolution water vapour observations can be a significant cause of analysis error and lead to poor initialization of an NWP model. The development of a GNSS

Corresponding author: <<John Le Marshall>>, <Bureau of Meteorology, GPO Box 1289 Melbourne Victoria>>
Email: <<j.lemarshall@bom.gov.au>>

based system to improve moisture analysis and forecasting over Australia is therefore an important strengthening of current high-resolution moisture analysis and forecasting capability and is anticipated to provide an improved basis for both moisture and precipitation forecasting (Ducrocq et al., 2002, Yan et al., 2008, Bennitt and Jupp, 2012, de Haan, 2013).

Moisture-related observations in the form of the GNSS ZTD are a relatively new source of mesoscale humidity information with ZTD being obtained from networks of ground-based GNSS receivers providing horizontally dense information on the distribution of total water *v*apour. An advantage of GNSS ZTD observations is that they are nearly continuous with high temporal resolution (15 minutes), and are useful in nearly all weather situations. In Australia these data are additionally important as they add valuable information in a data sparse region. Furthermore, we are currently in an environment where there is an increasing number of ground based GPS receivers, capable of providing this information, being established across Australia. As a result the availability of ZTD data across the continent is expected to increase considerably over the coming years.

Activity has already been focussed on improving the BoM's moisture analyses (see for example Le Marshall et al., 2014), however there still remains a requirement for improving the quality of moisture analyses particularly over land. These analyses can be improved, for example, by expanded use of METARS and Automatic Weather Stations, by better use of hyperspectral sounder data in the lower troposphere (eg Le Marshall et al., 2014, *op cit*) and by including improved specification of the surface infrared emissivity (W.L. Smith, Private Communication). Another way of improving moisture analysis is by the use of GNSS satellite to ground data.

In this study we wished to determine if the incorporation of GNSS ZTD data into the assimilation database can assist in the modelling of moisture and in particular in the modelling and prediction of rainfall. The addition of the ZTD data is expected to be of utility as it can estimate total water vapour to around 2 millimetres accuracy and is available in areas often devoid of middle and lower tropospheric moisture data. This has been studied in other works overseas with mixed results and these are noted in section 3. Australia presents a unique opportunity for this work because of the high density and coverage of the still expanding GNSS surface networks.

Here we have used an Australia wide network of GPS receiving stations to provide ZTD data every quarter hour/hour and have incorporated these data into Australian region scale and state scale data assimilation systems to improve moisture analysis and to provide high resolution forecasts over the Australian region, particularly Victoria. Related work has also

been done to show the utility of the ZTD data when used in conjunction with satellite sounding data, for example microwave sounding data, to improve moisture fields over the Australian region.

2 The GNSS Data Processing Systems

2.1 Background

The measured ZTD is the delay in reception of a signal from a GPS satellite which is directly overhead as a result of the presence of the neutral atmosphere and is expressed in terms of excess path length (Bevis et al. 1992). Slant path delays are mapped to the zenith using a mapping function, for example Neill 1996. ZTD is related to the refractivity along the signal path by

$$\text{ZTD} = 10^{-6} \int_{z_a}^{\infty} N \ dz$$

where z_a is antenna height (m) and N is the neutral atmosphere refractivity. Expanding N provides

$$\text{ZTD} = 10^{-6} \int_{Z_a}^{\infty} k_1 \, \rho R_d \ dz \ + 10^{-6} \int_{Z_a}^{\infty} \frac{R_d}{\varepsilon} \left(k_2 - \varepsilon k_1 + \frac{k_3}{T} \right) q \, \rho \ dz$$

where R_d = 287.05 J kg^{-1}K^{-1} is the gas constant of dry air, ρ is the water vapour density (kg m^{-3}) and ε= 0.62 is the ratio of molar weights. The empirical constants are k_1 = 77.6 K hPa^{-1}, k_2 = 70.4 K hPa^{-1} and k_3 = 373900 K^{2}hPa^{-1} (Thayer, 1974). ZTD has two components, the delay due to hydrostatic pressure and the delay due to the water vapour along the path (Bengsston et al., 2003). Minimisation of a cost function which takes account of the observed ZTD during the meteorological analysis improves the determination of atmospheric water vapour amount around the signal path.

The near real-time systems estimating the tropospheric parameters ZTD and ZTD gradients for Australia used here are run by RMIT University and Geoscience Australia. They require access to GNSS data/information in real-time or close to real time. The supporting data types required for GNSS data processing are: precise ultra-rapid GNSS satellites orbit and clock data, satellite differential code biases, global ionosphere maps, satellite health data, earth's pole offsets, receivers and satellite antenna phase centres, nutation data, sub-daily pole offsets, solid earth tide data, ocean tide data, ocean and atmosphere tide loadings.

These data types have been processed with Bernese GNSS Software 5.2 (Dach et al., 2007, Dach and Walser, 2015) and have been downloaded automatically each hour by the processing systems which also download and store RINEX (Receiver Independent Exchange Format) files with GNSS observation data.

2.2 The Sources of GNSS Observation data

There are a number of key sources of GNSS observational data that have been used for tropospheric parameter estimation for Australia/Victoria. The first one is the IGS (International GNSS Service) network, which for Victoria has 8 IGS stations located in or within 1000km radius from Victoria. The stations are: Ceduna, Hobart, Melbourne, Parkes, Mt Stromlo1, Mt Stromlo2, Sydney and Tidbinbilla. Another source is the APREF (Australia Pacific Reference Network) with 34 stations of the ARGN (Australia Reference Geodetic Network) located in or within the 1000 km radius from the Victoria. A third source is the GPSnet® network operated by the Victorian Government with 114 stations. The distribution of stations is seen in Figure 1. These sources provide a total of 146 stations. Access to these three networks in the case of RMIT University for example is organized in near real-time for IGS and APREF data by ftp download, and for the GPSnet® network in real-time, by the storing streams from all stations. Over the whole of Australia we have over 256 GNSS stations now available for this activity and the number is quickly increasing.
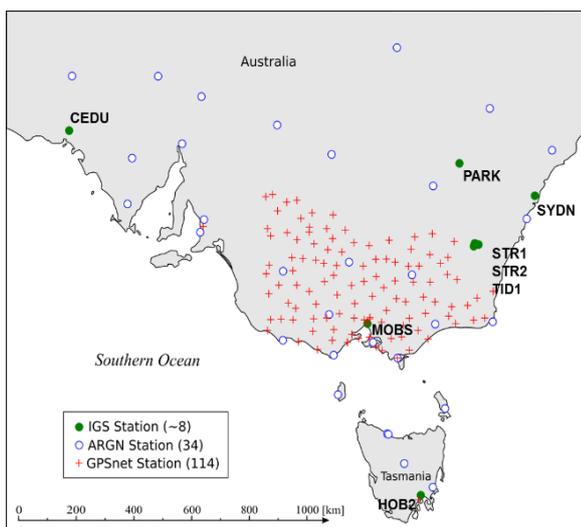

Figure 1(a). Map of stations around Victoria used for near real/real time processing as sources of GNSS data.
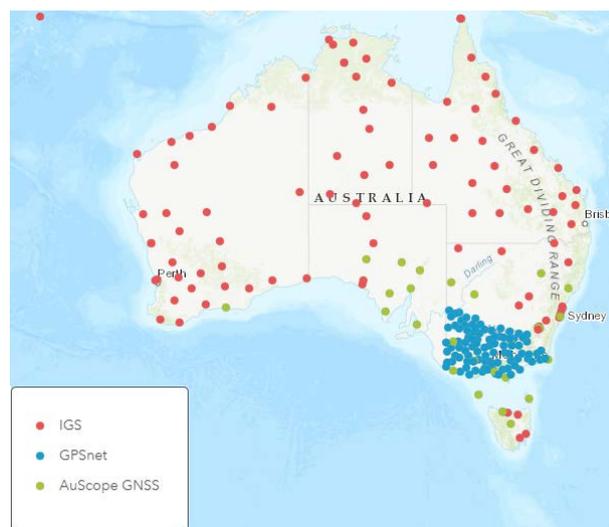
Figure 1(b). Map of stations around Australia used for near real/ real time processing as sources of GNSS data.

2.3 The RMIT University Processing Methodology

A number of processing scenarios were investigated with respect to ZTD estimation in real/near real-time at RMIT University. The first was use of the double difference (DD) solution without integer ambiguity resolution. The second method was use of the double-difference solution with ambiguity resolution. This method is slower because of multiple ambiguity estimations. The network solutions implemented were based on the standard Bernese RINEX to SINEX (Site Independent Exchange Format) automated processing scheme. The double-difference processing strategy included different ionosphere handling and ambiguity resolution methods dependent on baseline length. The Final ZTDs estimation was done using the Saastamoinen model (Saastamoinen, 1972) and GMF (Global Mapping Function) wet and dry mapping functions. The model for horizontal gradients of ZTDs was Chen and Herring (1997). Relative constraining of +/-3mm for ZTD was applied over a one hour interval to avoid "jumps" in tropospheric parameters.

In the double-difference scenario with fixed ambiguity resolution, the minimum constraint condition is applied over all epoch station coordinates. Reference coordinates of the ARGN and GPSnet stations are estimated from the solutions of the last 14 days with minimum constraint conditions on IGS station positions and velocities in separate Bernese scenarios. In the scenario without ambiguity resolution, heavy constraining on all stations coordinates (0.000001 m) is applied. It was found both solutions are viable and produce ZTDs of similar quality.

To smooth and improve the ZTD time-series, the joint estimations of ZTDs from the few last stored solutions are commonly made (Dousa, 2012). This approach was also applied to the near-real-time service, that is the stacking of the last 7 normal equation files stored by the Bernese software and to the re-estimation of troposphere parameters. The single window solution for an hour covered the last 6 hours and the stacked solution for the hour covered the last 7 normal equations and contained the ZTDs and gradients for the last 12 hours.

2.3.1 Quality assessment of the estimated ZTD

Initially the ZTD results were compared to the Rapid ZTD product from the CODE Analysis Centre (Switzerland) for the IGS network. Because no other processing centres were disseminating the ZTD results for ARGN and GPSnet® networks, the comparison was only possible on IGS stations. For the six stations processed the bias was mostly in the range +/-1.5mm and the standard deviation was mostly near to or below 6.5mm for the 77 day period studied (day 91 to 168 of 2015).

The fixed and float versions of the network processing services have been operating in real time since day 91 of 2015. Quality assessment of ZTDs was also undertaken with respect to FINAL IGS ZTD product for same 77 days. After consideration of results from comparisons with the CODE Analysis Centre Data and the FINAL IGS ZTD product it was decided to employ a double-differenced solution (DD), calculated using a 6-hour window with fixed ambiguity resolution for NWP application.
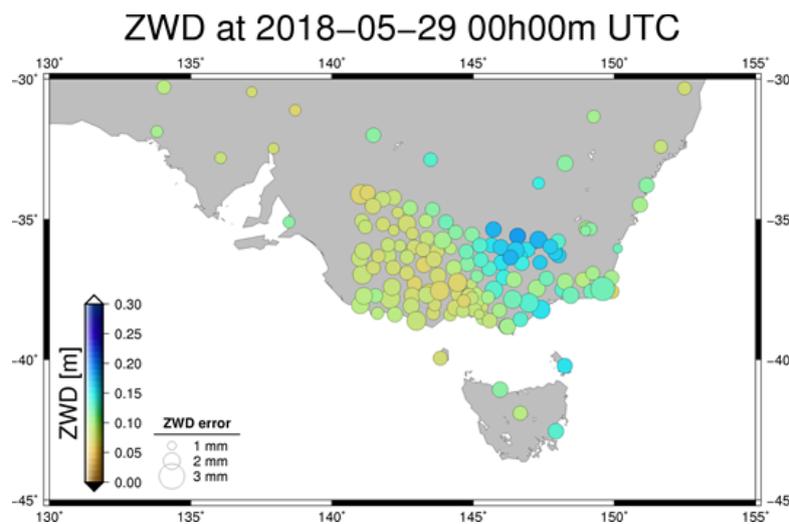

Figure 2 Zenith Wet Delay (ZWD) in metres over Victoria, calculated from ZTD at 00 UTC 29 May

Figure 2 shows a typical product from the RMIT University system, namely Zenith Wet Delay (ZWD) in metres over Victoria, calculated at 00 UTC 29 May 2018.

2.4 The Geoscience Australia Processing Methodology

Geoscience Australia (GA) routinely produces ZTD data. GA employs a Precise Point Positioning processing (PPP) strategy using the Bernese 5.2 software package. To estimate the near-real time ZTD, it relies upon the IGS Real Time clock products and IGS ultra-rapid (UR) orbits. ZTD estimates are provided every hour with a latency of approximately 40 minutes from approximately 160 stations around Australia. Here GA use a sliding window of 24 hours of raw observations obtained from real-time streams sourced from the ARGN, Auscope, South Pacific and LINZ GPS networks. To help validate the ZTD estimates GA also produce a rapid (R) solution, which relies upon the rapid IGS orbit and clock products. For the rapid solution GA processes over 600 stations from a global network dominated by stations in the Asia Pacific region. The system has been established in the Amazon Web Services (AWS) cloud to help aid in reliability and scalability.

The distribution of GNSS stations used by Geoscience Australia is shown in Figure 3. This is a subset of the stations in Figure 1(b), however the GA component of the data-base is still increasing.
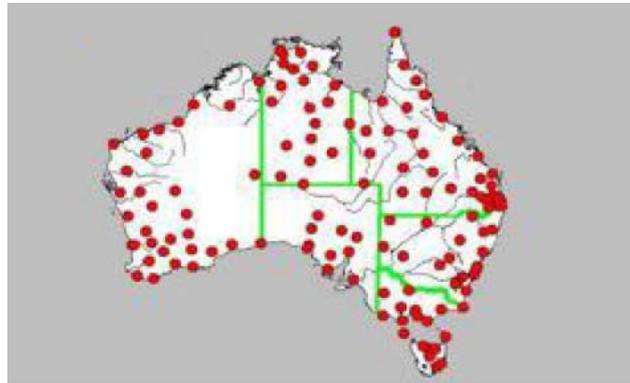

Figure 3. The distribution of GNSS stations processed by Geoscience Australia

2.4.1 Quality assessment of estimated ZTD

Comparison between PPP (IGS Rapid) and DD (IGS Final) ZTD data from Geoscience data was performed as part of basic testing. The derived ZTD from DD was the reference. The period of comparison was from day 200 to day 229, 2015 when the number of GPS stations was 110. There were 13 stations with root-mean-square (RMS) differences between 4-9 mm
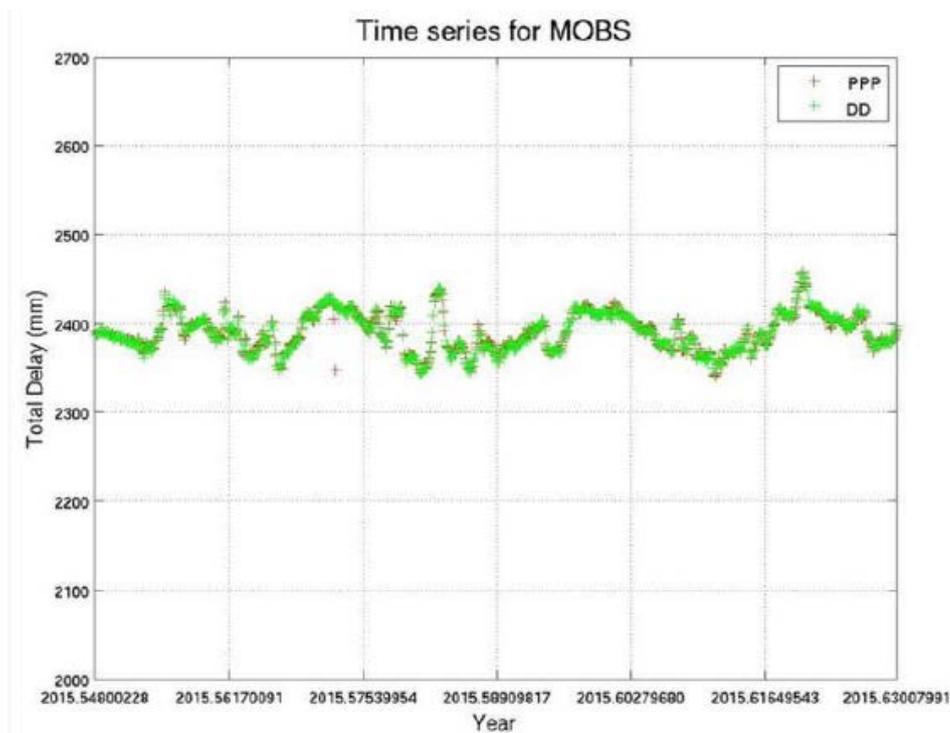

Figure 4. The results of comparison between PPP and DD processing methodologies for the Melbourne station.
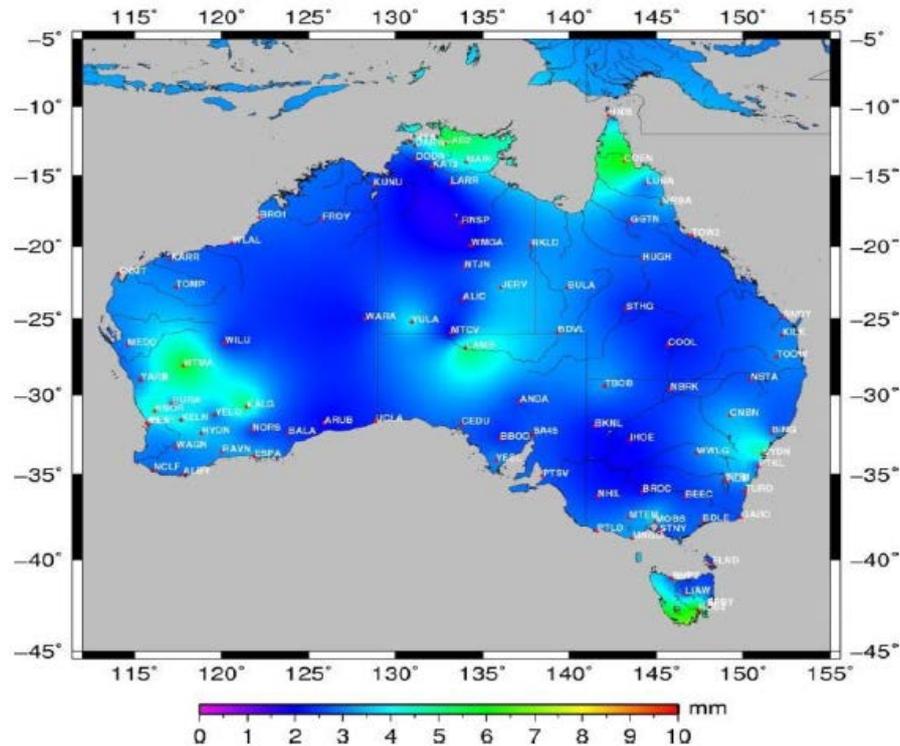
Figure 5. The distribution of RMS differences from the comparison of processing methodologies

when comparing PPP with DD results. The RMS differences for the others were between 1-4 mm. The results of testing showed good agreement between the two strategies. The Figure 4 is the comparison between PPP and DD for the MOBS (Melbourne) station. The distribution of RMS differences for all stations is shown in Figure 5. The UltraRapid (UR) orbit + IGS02 clock combination was chosen for near real time ZTD production.Output from the system during the period from 12-July-2016 to 31-July-2016 were evaluated. In general, around 93% of GPS stations can provide the UR ZTD derived from UR processing with less than 5% difference compared to R ZTD from daily processing.

Geoscience Australia has constructed a system and started routinely producing two ZTD estimation products by using the PPP strategy through Bernese software package. To estimate the near-real time ZTD, GA relies upon the IGS Real Time clock products and the IGS UltraRapid orbits. ZTD estimates derived from the sliding window of 24 hours of raw observations are provided every hour with a latency of approximately 40 minutes from approximately 160 stations.

Figure 6 shows a typical product from the GA system, namely Zenith Total Delay (ZTD) in millimetres over Mount Stromlo and Parkes, compared to the current operational non-data assimilating ACCESS-C2 and GA Rapid and UltraRapid Data.
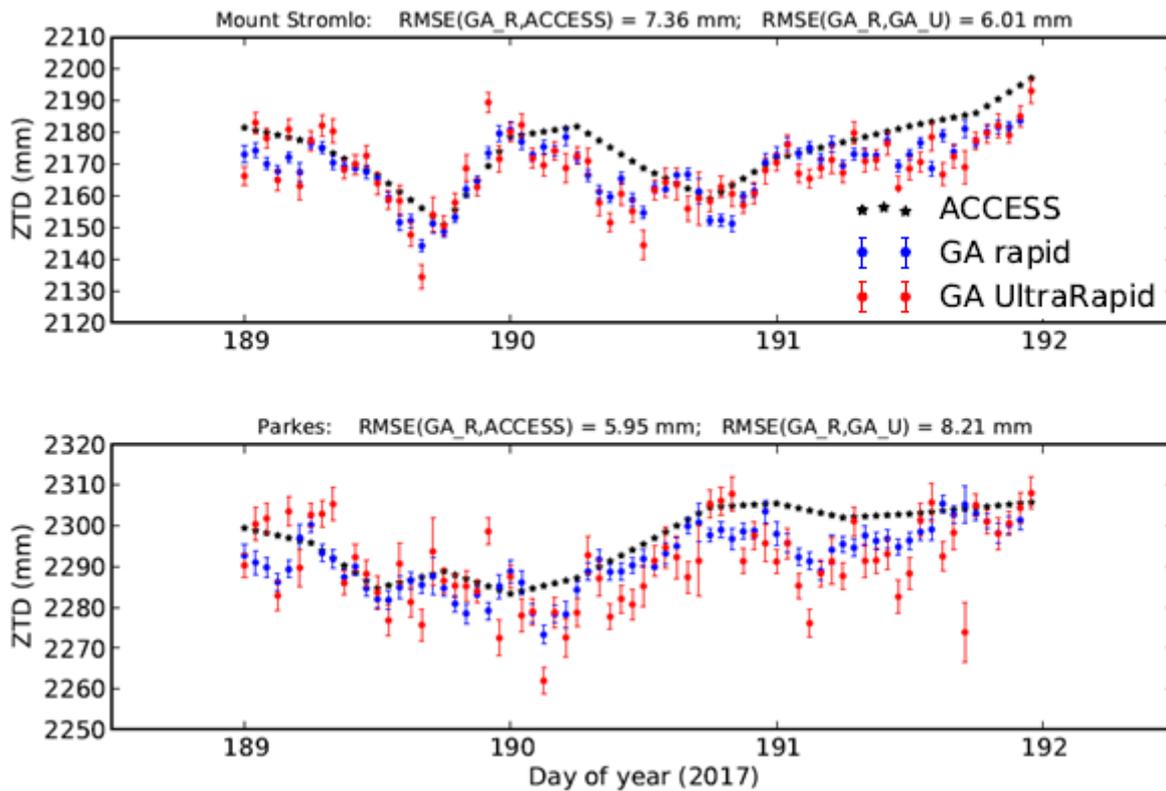
Figure 6   Zenith Total Delay (ZTD) in mm (millimetres) over Mount Stromlo and Parkes, compared to ACCESS-C2 for GA Rapid and UltraRapid Data processed by Geoscience Australia

3 The Assimilation of GNSS ZDT Data

The assimilation of ZTD observations in numerical weather prediction (NWP) has been described in several studies. A number of the studies have shown a positive impact of GNSS ZTD observations on NWP systems at a horizontal model grid resolution of the order of 10 km (De Pondeca and Zou, 2001; Vedel and Huang, 2004; Cucurull et al., 2004; Faccani et al., 2005; Poli et al., 2007; Macpherson et al., 2008; Yan et al., 2009a, b; Boniface et al., 2009; Benjamin et al., 2010; Shoji et al., 2011; Bennitt and Jupp, 2012).

Poli et al (2007) noted an improvement in synoptic scale circulation over 24 to 96 hours and some improvement in precipitation patterns. Yan et al. (2009) and Boniface et al. (2009) noted some positive impact on precipitation forecasts. MacPherson et al. (2008) noted positive impact on forecasts of precipitation amounts by assimilating ZTD observations into the Environment Canada regional NWP model. The complementary benefits of using GNSS data with other observation types has also been demonstrated in a number of studies (Cucurull et al., 2004; Sánchez-Arriola and Navascués., 2007; de Haan, 2013; Sánchez-Arriola et al., 2016). Initial assessments of the impact of the assimilation of these data at near kilometre

horizontal resolution demonstrate their potential impact and are recorded in studies such as Seity et al., 2011, de Haan, 2013 and Sánchez-Arriola et al., 2016. As a result of these and other studies GNSS ZTD data are now assimilated operationally at some operational NWP Centres.

3.1 The Data Assimilation System

The assimilation system used in this study is the Bureau of Meteorology's future operational ACCESS-C3 system. The ACCESS system was implemented as an update to the Bureau's NWP and climate modelling capabilities (Puri et al., 2012). The ACCESS system is based on the UK Met Office atmospheric model. It is used operationally in real time in the Bureau's National Operations Centre (NOC). The ACCESS-C3 system used here has a domain covering Victoria and Tasmania. It has a horizontal resolution of near 1.5 km stretching out to 4km at its border and it has 80 vertical levels. The ACCESS-C system uses the UK Met. Office unified model (UKUM) and the associated four-dimensional variational assimilation (4DVAR) analysis system, the UK Met. Office observation processing system (OPS) and the surface fields processing system (SURF). An update to the SST (Sea Surface Temperature) and soil moisture was performed daily. The SST update came from the operational Regional SST product (Beggs et al. 2011), and the soil moisture came from the ACCESS-G analysis, with higher-resolution features provided by the soil property ancillaries.

 The ACCESS-C suite runs with a 1-hour cycle, 24 times per day (0000 UTC, 0100 UTC, 0200 UTC, 0300 UTC etc.), using observations from Observation Processing System in the 4DVAR analysis. The domain is nested in 12-km resolution ACCESS-R2 with boundary conditions updated at 0300UTC, 0900UTC, 1500UTC and 2100UTC.

3.2 The Data Assimilation Methodology

An initial data assimilation trial with GNSS data predominantly available from the high-density Victorian network examined a limited period in November/December 2015. The ACCESS-R 12km resolution forecast model was used with 4DVAR (Puri et al., 2013). The ZTD observations values were assimilated directly into the model with the ZTD observation operator estimating the background ZTD using a model short-range forecast (Rawlins et al., 2007). The study was completed in 2015.

After an assessment of the output from this study it was decided to set up a network collection and processing system suitable for operational use to provide ZTD data for the 1.5km high resolution data assimilating ACCESS C-3 forecast system, ACCESS-C3.

An example of the impact of these local GNSS ZTD data in ACCESS-C3 is provided in this study for a recent very heavy rainfall event over South East Australia, in particular over Victoria. This was a difficult operational forecast. In the data impact tests the impact of using local GNSS ZTD observations on forecast accuracy over South East Australia/Victoria was examined. For the period studied, particularly 29 November to 4 December 2017, four-dimensional variational assimilation was employed to assimilate the ZTD observations into the ACCESS system, namely the Victorian Capital City Model (AC-CESS-C3), which provided forecasts out to two days. Both RMIT University and Geoscience Australia (GA) data were used, which provided a degree of redundancy and also protected against the effects of some problems, for example, clock errors, which may affect one system (PPP) more than the other. Station/processing-centre biases were removed from the ZTD observations generated by RMIT University and Geoscience Australia (GA) before the assimilation was undertaken. This was done using monthly average biases from matchups computed from the observed ZTD data and forecast model fields at GNSS observation sites. An example of the bias associated with these matchups is seen in Table 1.

In this study the forecasts for the control run used the full next generation operational data base to be used at the Bureau of Meteorology for the third generation ACCESS model, which included the data listed in Table 2. The experimental run was identical to the control run in all aspects except that it had the local ZTD data added to the full operational database used in the assimilation/analysis step. Typically, in the first assimilation period, 150 to 250 ZTD estimates/observations were provided to the system every hour.

Station Name	Location	Bias	Nobs
HOB2-GA01	Hobart-TAS	0.0028206	1321
HOB2-SPAC	Hobart-TAS	0.0065149	820
GABO-SPAC	Gabo Island-VIC	-0.0037643	1297
MOBS-GA01	Melbourne-VIC	0.0034380	1337
MOBS-SPAC	Melbourne-VIC	0.0013783	851
MTEM-SPAC	Mt. Emu-VIC	0.0014467	1298
NHIL-SPAC	Nhil-VIC	-0.0010808	1293
STR1-GA01	Mt Stromlo-ACT	0.0021986	1328
SA45-SPAC	Saltia-SA	0.0035503	546
SYDN-GA01	Sydney-NSW	0.0059522	1331
SYDN-SPAC	Sydney-NSW	0.0067022	875
PARK-GA01	Parkes-NSW	0.0069646	1302
PERT-GA01	Perth-WA	-0.0001268	1335
RSBY-GA01	Rosslyn Bay-QLD	0.0129446	1252
TOW2-GA01	Townsville-QLD	0.0091179	1320
JAB2-GA01	Jabiru-NT	0.0197600	1128

Table 1. Bias and Standard Deviation (m) of GNSS ZTD observations compared to ACCESS-R at selected GNSS Sites, 19 November – 19 December 2017

Surface synoptic observations	Atmospheric Motion Vectors	CrIS radiances
Radiosonde observations	Scatterometer Winds	IASI radiances
Aircraft observations	ATOVS radiances	GPSRO bending angles
Doppler radar radial winds	AIRS radiances	ATMS and AMSU radiances

Table 2. Key conventional observations and earth observations from space used in the Next Generation observational data base for the ACCESS-C3 suite.

4 The Assimilation of GNSS based ZTD observations in ACCESS C3 over Victoria, 29 November – 4 December 2017

ZTD observations have been assimilated into the Bureau's future operational 1.5km ACCESS-C3 forecast model over South Eastern Australia/Victoria between 29 November and 4 December, 2017. This period was chosen because it contained examples of no rain, light rain and flooding rain and had proved to be a difficult forecast period for operations. Incorporation of the additional moisture information contained in the ZTD data in the ACCESS-C3 analysis was anticipated to improve the C3 model's moisture analysis and hence provide improved initial conditions for the C3 model's forecasts. As noted, some investigators have reported to date that the use of the GNSS ZTD data has provided improvements in numerical modelling in relation to surface moisture and also rainfall prediction. In this case we have examined these and other elements over SE Australia/ Victoria during the period of the study.

In relation to surface /lower tropospheric moisture, the GNSS observations have changed these model fields. An examination RMS Observed minus Background (O – B) Relative Humidity (the amount of water vapour present expressed as a fraction of the water vapour needed for saturation) statistics (Figure 7) indicates the surface relative humidity RMS O-B value for the case with GNSS ZTD is slightly smaller than that for the case not using the ZTD data. In this case there also appears to be a small temporal delay in features of the relative humidity O-B versus time trace for the no GNSS ZTD data case.
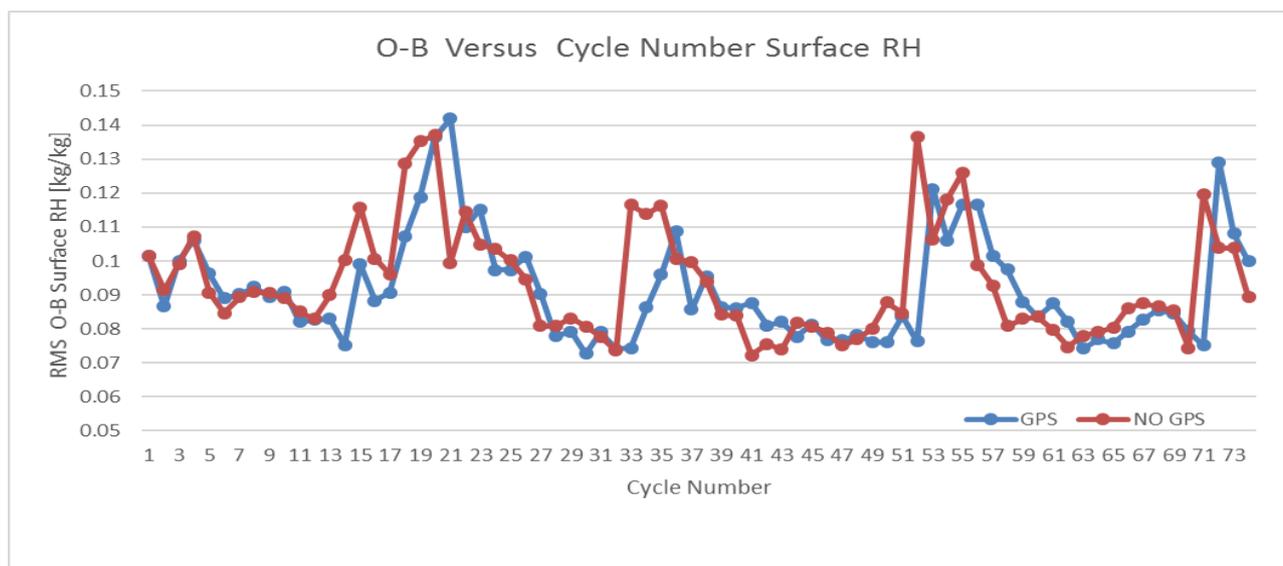

Figure 7. The variation of O-B for surface relative humidity (see text) between the third and fifth of December 2017 when GNSS ZTD data are assimilated (blue) compared to when ZTD data are not used (red).

For model level 20 (~2km altitude) relative humidity, the O-B values are smaller more often than not when ZTD data has been used. It should be noted this is a quite small sample however, with results not to be generalised. The comments reflect only the reasonable nature of the results.

In relation to precipitation, the impact of the ZTD data on the ACCESS C3 forecasts is qualitatively visible in Figures 8, 9 and 10. The quantitative impact of the ZTD data is seen in Figures 11 and 12 through use of the Fractions Skill Score (Roberts and Lean, 2008). In Figure 8(a) rainfall totals between 00UTC 30 November and 00UTC 1 December from the Bureau's operational AWAP system (Jones et al., 2009) are shown (note colour shading for totals ranges from *4mm to 400mm* of rain). The forecast rainfall totals for the same period for the control case (no ZTD data) Figure 8 (b), and for the experimental case (with ZTD data) Figure 8 (c) show different distributions of accumulated rainfall over western and central Victoria. The forecast rainfall maximum near Portland (on the left edge of the Victorian coastline) is a little better positioned in the case which used ZTD data (Figure 8 (c)), while the rainfall maximum to the NE of Melbourne is also a little better depicted in the forecast with ZTD data.

In Figure 9(a) rainfall totals between 00 UTC on 1 December and 00 UTC on 2 December as analysed by the operational AWAP system are shown (note colour shading for totals ranges from *4mm to 400mm* of rain). The forecast rainfall totals between 00 UTC on 1 December and 00 UTC on 2 December for the control case Figure 9 (b) and for the experimental case with ZTD Figure 9 (c) again show differences in the distributions of forecast rainfall, this time over eastern and central Victoria. It can be seen that the case that used ZTD data has produced more realistic rainfall coverage over the western part of the State of Victoria. The heavy rain (> 50 mm, light blue) to the north-east of Melbourne is a little better positioned , closer to Melbourne, for the system which used ZTD data.

In Figure 10(a) rainfall totals between 00 UTC on 1 and 2 December as analysed by the operational AWAP system are again shown, however the colour shading for the lower rainfall totals are changed, to highlight the 0.*4mm to 40mm* lower rainfall areas. The forecast totals between 00 UTC on 1 and 2 December for the control case Figure 9 (b) and for the experimental case with ZTD Figure 9 (c), clearly show differences in the distributions of the forecast lighter rainfall over eastern and central Victoria. It is apparent that the forecast with ZTD data has produced better light rainfall coverage over the eastern part of the State of Victoria than the control forecast.. The heavy rain ($\geq$ 27 mm) over Western Victoria is coloured red.
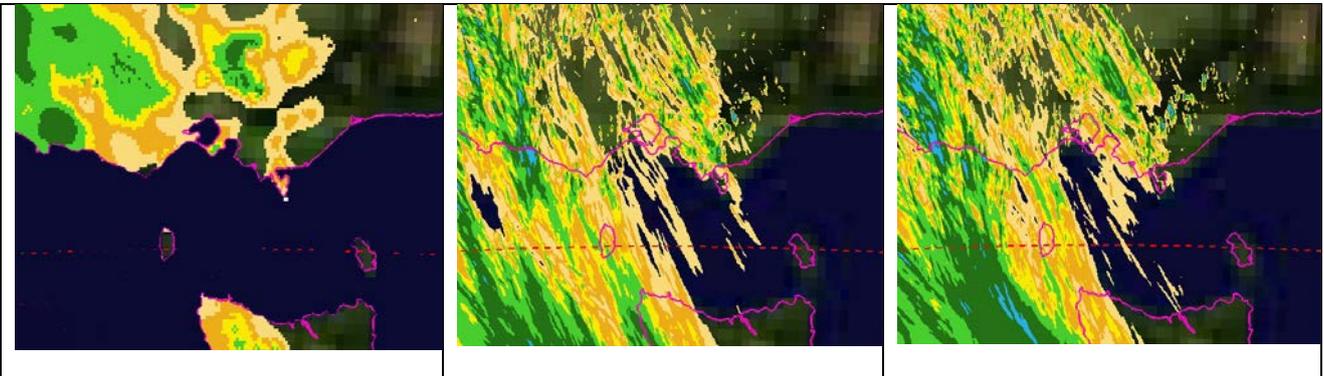
Figure 8. 24 hour rainfall totals. 8(a-left) totals between 00 UTC 30 November and 00 UTC 1 December from the operational AWAP system, (b-centre) forecast totals for the control system for the same period (no ZTD data) and (c-right) forecast totals for the experimental system (including ZTD data). Colour Scale versus rainfall shown in Fig 11(a)
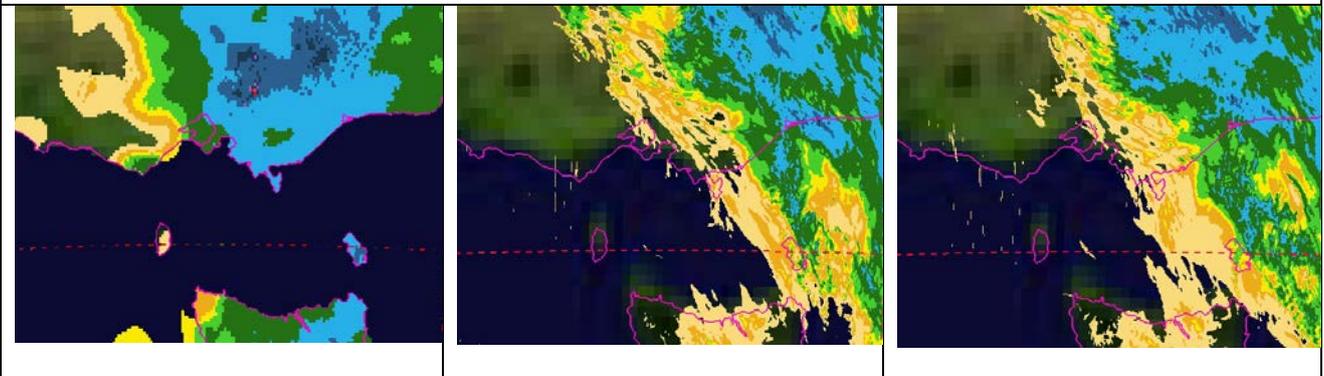

Figure 9. 24 hour rainfall totals. 9(a-left) totals between 00 UTC on 1 and 2 December from the operational AWAP system, (b-centre) forecast totals for the control system for the same period (no ZTD data) and (c-right) forecast rainfall totals for the experimental system (including ZTD data). Colour Scale versus rainfall shown in Fig 11(a)
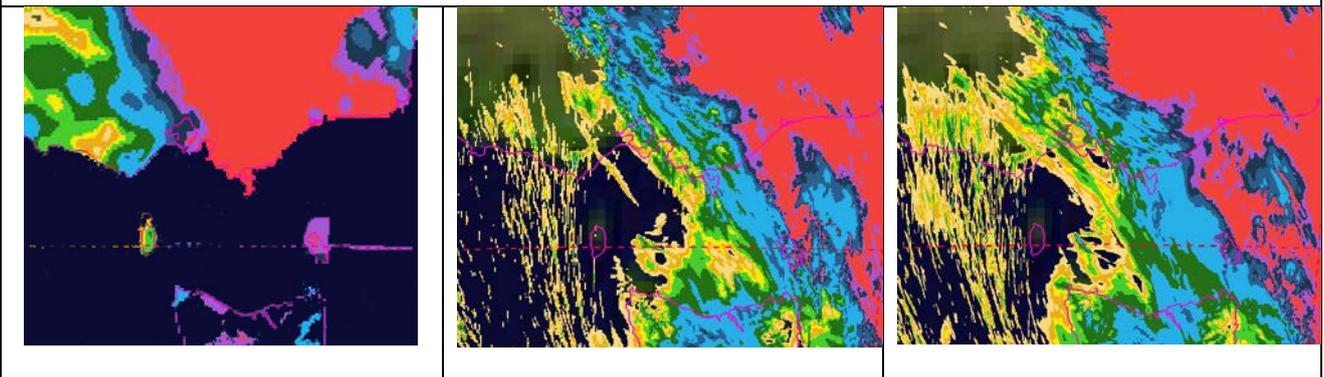

Figure 10. 24 hour rainfall totals as in Figure 9 (a), (b) and (c). Colour Scale versus rainfall shown in Figure 11(b). Rain totals ranging from 0.4 to ≥ 40mm.
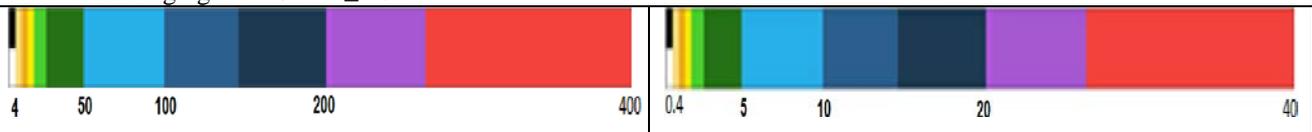

Figure 11(a-left) 24 hour rainfall totals by colour for Figures 8 and 9, Figure 11 (b-right) 24 hour rainfall totals by colour for Figure 10.

In addition to qualitative/synoptic assessment of the rainfall forecasts, quantitative assessment of the rainfall accumulation fields has been undertaken using the Fractions Skill Score (Roberts and Lean, 2008, Mittermaier and Roberts, 2010). The Fractions Skill Score ranges from 0 (complete mismatch) to 1 (perfect match). If no events are forecast and some occur, or some occur and none are forecast the score is 0. This metric was chosen because of its utility in the assessment of high-resolution (here 1.5 km resolution) forecast rain fields. It is now used routinely in the BoM and in other weather services to assess the utility of high-resolution rainfall forecasts. Its capacity to gauge the utility of the rainfall forecasts at differing scales and its ability to guard against the 'double penalty' problem in rainfall forecast verification is a key reason for the choice. A detailed description of the characteristics and benefits of the method are contained in the two references cited above. In this study, rainfall accumulations for 12 and 18 hours forecasts at 00, 06, 12 and 18UTC from ACCESS C-3 have been examined in terms of Fractions Skill Score using the Global Precipitation Measurement mission, IMERG (Integrated Multi-satellite Retrievals for GPM) -L (late) late run rainfall product (Huffman et al., 2015) for verification.
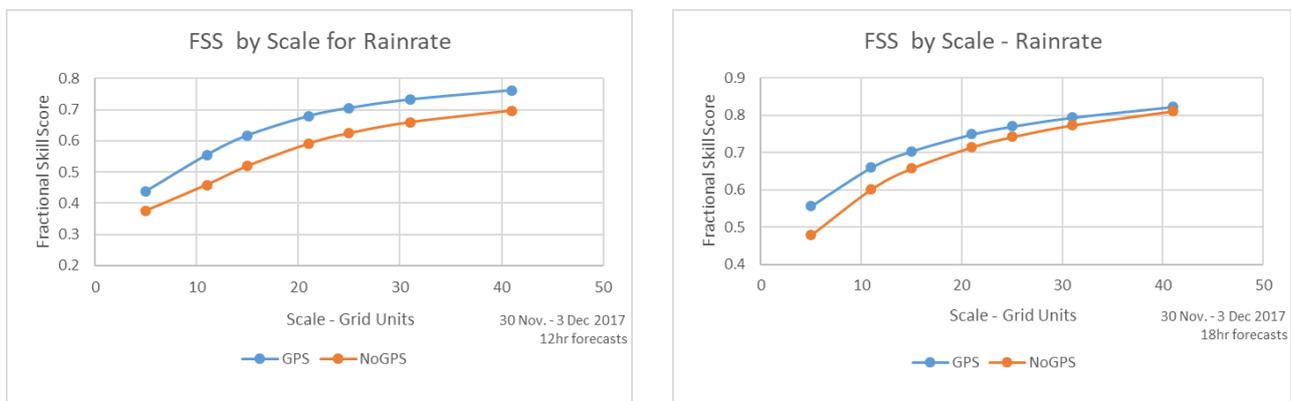

Figure 12 (a- left) Fractions Skill Score versus Scale (in grid units) for 12 hour forecasts during the period 30 November to 4 December 2017, for forecasts where GPS data was and was not included in the forecast data base. Figure 12 (b-right) Fractions Skill Score versus Scale for 18 hour forecasts during the same period for forecasts where GPS data was and was not included in the forecast data base.

Figure 12(a) shows the Fractions Skill Score versus Scale (in grid units) for 12 hour forecasts during the period 30 November to 4 December 2017, for forecasts where GPS data was and was not included in the forecast base. For the period of the trial, the 12 hour forecast has shown improvement overall on average, at all grid scales when GPS data is used. It was also found

for this period that the use of GPS data on average resulted in improved forecasts for each rainfall accumulation category (the categories are for accumulations greater than .5 mm, 1 mm, 4 mm, 8 mm, 12 mm, 16 mm and 41mm). Rainfall forecasts for 18 hours were also examined for the same period. Figure 12(b) shows the Fractions Skill Score versus Scale for the same period. Again, for the period of the trial, the 18 hour forecasts have shown improvement on average, at all scales and it was also found that the forecast done using GPS data, on average result improved forecasts for each rainfall accumulation category. Figure 13 shows the number of improved forecasts with ZTD data by scale when GPS data is used/not used in the forecast database. For the case studied at all scales the number of forecasts improved by ZTD data exceeded the number not improved.
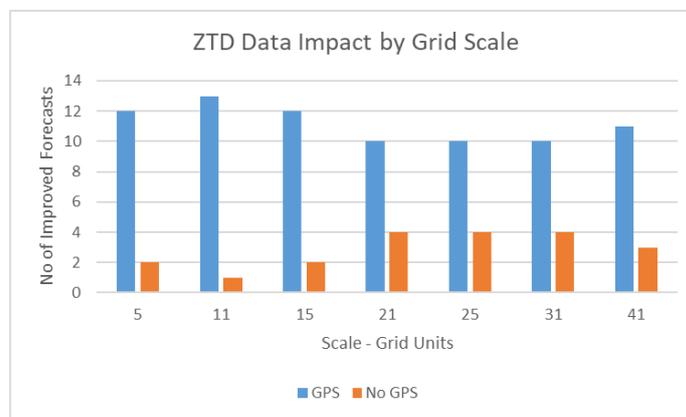

Figure 13 ZTD data impact by grid scale shown through number of improved forecasts when GPS is or is not used in the forecast process.

The results from this trial, which have been examined qualitatively/synoptically and also been examined quantitively using the Fractions Skills Score show the reasonableness of the forecasts and demonstrate the potential for improving rainfall forecasts over south-eastern Australia with the use of GNSS based ZTD data.

5 Conclusions

For the first time ZTD data provided by GNSS missions have been used in NWP to enhance moisture specification of the atmosphere at up to near 40 kilometres resolution across South Eastern Australia. These observations have an accuracy

(often equivalent to < 2mm rms error in total water vapour) which enables them to be of potential benefit for NWP and to be of value in the Australian region, which is in the data sparse southern hemisphere. Here we have ued ZTD, produced in real time/close to real time by RMIT University and Geoscience Australia (GA) and this has resulted in an enhanced database for the specification of moisture fields in the ACCESS C3 system. The improved database has resulted in improvements to 12 and 18 hour rainfall forecasts which have been measured using the Fractions Skill Score. The impact of the data will be further documented in part two of this paper as the C3 model is used in different seasons, as the networks providing ZTD data are further expanded and more forecasts using ZTD data are produced.

Of note is that these data are little affected by cloud and precipitation, in many areas are of high horizontal resolution and are near continuous in time. As a result, their use is well suited to NWP and climate studies. Their characteristics and their availability also complements the use of space based meteorological sounders over land, where we have found a significant improvement in sounding moisture fields from using the ZTD data in conjunction with, for example, space based or ground based microwave sounder radiances. In a related study, we have used synthetic ZTD/TPW (total precipitable water vapour) and microwave radiances sensed from the surface and space-based instruments to measure moisture profiles. Improvements in the retrieved profiles were found by solving the RTE (radiative transfer equation) using a non-linear solver with a GFS (Global Forecast System) 6-hour first guess. This use of ZTD data is found to provide a constraint on the total moisture fields which improves the moisture profile in an RMS sense and allows the ZTD data to potentially reduce bias/errors in the total precipitable water field for use in NWP and in climate studies. In effect, it is anticipated the small errors of these observations will improve the absolute accuracy of analyses/reanalyses. Both these aspects are of importance in climate studies.

We also noted the comparison of ZTD observations with radiosonde moisture measurements indicates their utility for extending the monitoring of atmospheric moisture from around radiosonde network sites, to a fuller monitoring across the Australian region with new information including trends being revealed. In essence we believe that ZTD observations can delineate total water vapour/moisture trends away from radiosonde sites and importantly allow extension of the domain of climate quality moisture observations into data sparse areas often devoid of conventional upper air moisture information. This would indicate that ZTD data have the potential make a very important and unique contribution to vital tasks such as climate monitoring, adding significantly to the spatial and temporal coverage provided by the radiosonde network.

6 The Future

The use of GNSS ZTD data in Australian meteorology, for research and operational activities is expanding. In the Australian region GNSS ZTD observational data have the potential to improving meteorological analyses by providing timely atmospheric moisture information through the lower troposphere. Because of their level of accuracy, their addition to the meteorological database enables improved specification of the moisture fields in particular in the Australian region and experience would suggest improved predictability both within the region and beyond. Results point to the increasing utility of these plentiful and timely data, which will be used in conjunction with radiosonde observations, advanced sounders, surface synoptic data and other sources of moisture information across the region.

In conclusion it is important to note Australia has already a very dense coverage of GPS receiving stations and that this number is planned to increase in coming years as a result of increasing use of these signals for precision positioning. This is expected to enable improved moisture analysis and is expected to improve the quality of numerical prediction across the continent. The improved moisture data also has the potential to be used in the solution for exact position determination.

References

Beggs H., Zhong A., Warren G., Alves O., Brassington G. and Pugh T. 2011. RAMSSA—An operational, high-resolution, Regional Australian Multi-Sensor Sea surface temperature Analysis over the Australian region. Australian Meteorological and Oceanographic Journal., 61 (1), 1-22.

Bengtsson, L., and Co-authors. 2003. The use of GPS measurements for water vapour determination. Bull. Amer. Meteor. Soc., 84, 1249–1258.

Benjamin S. G., Jamison B.D., Moninger W.R., Sahm S.R., Schwartz B.E. and Schlatter T.W. 2010. Relative short-range forecast impact from aircraft, profiler, radiosonde, VAD, GPS-PW, METAR and mesonet observations via the RUC hourly assimilation cycle. Mon. Weather Rev., 138, 1319–1343.

Bennitt, G. and Jupp A. 2012, Operational Assimilation of GPS Zenith Total Delay Observations into the Met Office Numerical Weather Prediction Models, MWR, 140, 2706 – 2719.

Bevis, M., S. Businger, T. Herring, C. Rocken, R. Anthes, and Ware R. 1992. GPS meteorology: Remote sensing of atmospheric water vapor using the Global Positioning System. J. Geophys. Res., 97, 15 787–15 801.

Boniface K. , Ducrocq V. , Jaubert G. , Yan X. , Brousseau P. , and co-authors. 2009. Impact of high resolution data assimilation of GPS zenith delay on Mediterranean heavy rainfall forecasting. Ann. Geophys., 27, 2739–2753.

Chen, G. and Herring T.A. 1997, Effects of atmospheric azimuthal asymmetry on the analysis of space geodetic data, J. Geophys. Res., 102(B9), 20489–20502.

Cucurull, L., Vandenberghe F. Barker D. Vilaclara E. and Rius A. 2004. Three-dimensional variational data assimilation of ground-based GPS ZTD and meteorological observations during the 14 December 2001 storm event over the Western Mediterranean Sea, Mon. Wea. Rev., 132, 749–763.

Dach, R., Hugentobler, U., Fridez, P. and Meindl M. (ed.) .2007. Bernese GPS SoftwareVersion 5.0. User Manual. Astronomical Institute, University of Bern. http://www.bernese.unibe.ch/docs50/DOCU50.pdf

Dach, R., and Walser P. 2015. Bernese GNSS Software Version 5.2 Tutorial. Processing Example, Introductory Course, Terminal Session. Astronomical Institute, University of Bern. http://www.bernese.unibe.ch/docs/TUTORIAL.pdf ;

De Haan, S. 2013. Assimilation of GNSS ZTD and radar radial velocity for the benefit of very-short-range regional weather forecasts. Q. J. R. Meteorol. Soc., 139, 2097–2107.

De Pondeca, M.S. and Zou X. 2001. A case study of the variational assimilation of GPS Zenith Delay observations into a mesoscale model, J. Climate Appl. Meteor.,40, 1559–1576.

Dousa, J. and Bennitt, G. 2013. Estimation and evaluation of hourly updated global GPS Zenith Total Delays over ten months. GPS Solut. 17, 453–464.

Ducrocq, V., Ricard, D. Lafore, J. P., and Orain F. 2002. Storm-Scale Numerical Rainfall Prediction For Five Precipitating events over France: On the Importance of the initial humidity field, Weather Forecast, 17, 1236–1256.

Faccani, C., R. Ferretia, R. Pacione, T. Paolucci, F. Vespe, and Cucurull L. 2005. Impact of a high density GPS network on the operational forecast. Adv. Geosci., 2, 73–76

Huffman, G. J., Bolvin, D. T., Braithwaite, D., Hsu, K., Joyce, R., Kidd, C., Nelkin, E. J., and Xie, P. 2015. Algorithm Theoretical Basis Document (ATBD) Version 4.5. NASA Global Precipitation Measurement (GPM) Integrated Multi-satellitE Retrievals for GPM (IMERG), https://pmm.nasa.gov/sites/default/ files/document_files/IMERG_ATBD_V4.5.pdf

Jones, DA, Wang, W. and Fawcett R. 2009.High-quality spatial climate data-sets for Australia. Australian Meteorological and Oceanographic Journal, 58, 233-248.

Le Marshall, J., Jung, J., Lee J., Barnet C., and Eric S. Maddy. 2014. Improving Tropospheric and Stratospheric Moisture Analysis with Hyperspectral Infrared Radiances. Aust. Meteor. and Ocean. Jnl., 64, 283-288.

Mittermaier, M. and Roberts N. 2010. Intercomparison of spatial forecast verification methods: identifying skillful spatial scales using the fractions skill score. Wea. Forecasting, 25, 343-354.

Neill, A. E. 1996. Global Mapping for the Atmospheric Delay at Radio Wavelengths. Journal of Geophysical Research 111(B2):3227-3246.

Poli P, Moll P, Rabier F, Desroziers G, Chapnik B, Berre L, Healy S B, Andersson E. and Guelai F. Z. E. 2007. Forecast impact studies of zenith total delay data from European near real-time GPS stations in Meteo France 4DVAR, J. Geophys. Res., 112 (D06114), 1–16.

Puri, K., Dietachmayer, G., Steinle, P., Dix, M., Rikus, L., Logan, L., Naughton, M., Tingwell, C., Xiao, Y., Barras, V., Bermous, I., Bowen, R., Deschamps, L., Franklin, C., Fraser, J., Glowacki, T., Harris, B., Lee, J., Le, T., Roff, G., Sulaiman, A., Sims, H., Sun, X., Sun, Z., Zhu, H., Chattopadhyay, M., and Engel, C. 2013. Implementation of the initial ACCESS Numerical Weather Prediction system. *Aust. Met. Oceanogr. J.,*63, 265-284.

Rawlins, F., Ballard, S.P., Bovis,K.J., Clayton, A. M., Li, D., Inverarity, D., Lorenc, A. and Payne, T. J. 2007. The Met Office Global 4-Dimensional Data Assimilation Scheme. Quarterly Journal of the Royal Meteorological Society, 133, 347-362

Roberts, N.M. and Lean H.W. 2008. Scale-selective verification of rainfall accumulations from high-resolution forecasts of convective events. *Mon. Wea. Rev.*, 136, 78-97.

Saastamoinen, J. 1972. Atmospheric Correction for Troposphere and Stratosphere in Radio Ranging of Satellites. Geophysical Monograph. American Geophysical Union, Washington D.C, pp 247-252.

Sánchez-Arriola, J. and Navascués B. 2007, Report on surface moisture impact study. EU-FP5 TOUGH project deliverable D31, Available online at http://web.dmi.dk/pub/tough/deliverables/d31-rh2-impact.pdf.

Sánchez-Arriola, J, Lindskog M, Thorsteinsson S and Bojarova J. 2016. Variational Bias Correction of GNSS ZTD in the HARMONIE Modeling System. J. Appl. Meteor. Climatol, doi:10.1175/JAMC-D-15-0137.1.

Seity Y,Brousseau, P, Malardel S, Hello G, Benard P, Bouttier F, Lac C, Masson V (2011), The AROME-France Convective-Scale Operational Model,Mon. Wea. Rev., 139, 976–991.

Shoji, Y., Kunii M. and Saito K. 2011. Mesoscale data assimilation of Myanmar cycloneNargis. Part II: Assimilation of GPS-derived precipitable water vapor. J. Meteorol. Soc. Japan 89: 67–88.

Thayer G. D. 1974. An improved equation for the radio refractive of air. *Radio Sci*. **9**, 803-807.

Vedel, H., and Huang X.-Y. 2004. Impact of ground based GPS data on numerical weather prediction. J. Meteor. Soc. Japan, 82, 459–472.

X. Yan, Ducrocq, V., Poli1, P., Jaubert, G.and Walpersdorf A. 2008, Mesoscale GPS Zenith Delay assimilation during a Mediterranean heavy precipitation event, Adv. Geosci., 17, 71–77.

Yan, X., Ducrocq, V., Poli, P., Hakam, M., Jaubert, G. and Walpersdorf A. 2009a. Impact of GPS zenith delay assimilation on convective-scale prediction of Mediterranean heavy rainfall. J. Geophys. Res., 114, D03104, doi:10.1029/2008JD011036.

Yan, X., V. Ducrocq, G. Jaubert, P. Brousseau, P. Poli, C. Champollion, C. Flamant, Boniface K. 2009b, The benefit of GPS zenith delay assimilation to high resolution quantitative precipitation forecasts: a case-study from COPS IOP 9, Q. J. Roy. Meteor. Soc., 135, 644, 1788-1800.