2.3 ASSIMILATION OF GROUND-BASED GPS OBSERVATIONS IN THE CANADIAN REGIONAL ANALYSIS AND FORECAST SYSTEM

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1. INTRODUCTION

Microwave signals from Global Positioning System (GPS) satellites received at ground-based GPS receivers experience refraction as they pass through the atmosphere. This refraction reduces signal speed relative to vacuum, resulting in a delay in reception of the signal at the receiver. This delay is a nuisance parameter that must be estimated to obtain precise point positions with GPS.

The delay due to the atmosphere directly above a location, called the zenith tropospheric delay (ZTD), is estimated quite accurately in the processing of data from ground-based GPS receivers with specialized geodetic software (e.g. GAMIT, GIPSY, Bernese). The ZTD is the time delay expressed in terms of excess path length (m or mm) and depends on integrated water vapour (IWV) and surface pressure. Given surface pressure and temperature measurements, ZTD observations from GPS sites provide an all-weather measure of IWV (Bevis et al, 1992). Inter-comparison studies (e.g. Deblonde et al, 2005) show that precipitable water (PW) derived from 2-week latency ZTD observations is of comparable accuracy to that obtained from radiosondes (error of ~2 mm).

The Meteorological Research Branch (MRB) is evaluating ZTD observations for inclusion in the data assimilation and forecast systems of the Canadian Meteorological Centre (CMC). Since August 2004, near real time (NRT) observations from the US NOAA Environmental System Research Laboratory (ESRL) network of GPS receivers have been received at CMC and monitored by MRB. Assimilation experiments have been carried out with the observations and a modified version of the CMC regional three-dimensional variational (3D-Var) data assimilation and forecast system. Results of the monitoring will be presented and assimilation tests discussed.

2. GPS OBSERVATIONS

The observation of interest from ground-based GPS receivers is the zenith tropospheric delay ZTD. The ZTD is related to surface pressure (P_S) and PW as follows

$$ZTD = f_1(\varphi, H)\, P_S + f_2(T_m)\, PW \qquad (1)$$

where φ is the latitude, H is the height of the GPS antenna above the geoid, and T_m is vapour-weighted column mean temperature (which can be estimated from surface temperature). Typical values of f_1 and f_2 are 2.3 mm hPa^{-1} and 6.2 respectively. Typical values of sea-level P_S (1000 hPa) and PW (25 mm) give a total delay ZTD of 2.4 m.

Accuracy at the mm level for ZTD estimates is necessary for numerical weather prediction (NWP). Estimation of ZTD with such accuracy requires knowledge of the precise positions (orbits) of all GPS satellites in view at each site as well as sufficiently accurate a-priori GPS receiver antenna locations (particularly height). As precise orbits are only known after the fact, forecast orbits must currently be used for NRT applications. Errors in the orbits and antenna locations are primary error sources for ZTD estimates.

Some GPS sites are equipped with automatic surface weather stations, which provide frequent reports of pressure, temperature and relative humidity (RH), referred to collectively as GPS Met. Surface pressure and temperature can be used to compute PW from ZTD with (1). Over 95% of the sites comprising the NOAA/ESRL GPS network are so equipped.

The results presented here were obtained with NRT observations from the NOAA/ESRL GPS network from August 2004 to September 2005. The network will be referred to hereafter by its former name NOAA/FSL (for NOAA Forecast Systems Laboratory), which was recently changed to ESRL. The network is shown in Figure 1.

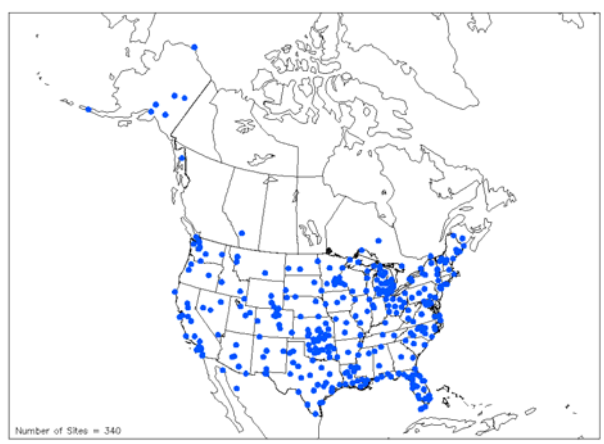

Figure 1: The NOAA/FSL GPS network: All sites (340) reporting from August 2004 to September 2005

Observations of ZTD, PW, and GPS Met are available every 30 minutes. The ZTD is estimated by NOAA/ESRL with the GAMIT software and a sliding-window approach (Foster et al, 2005). The PW

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observations derived from ZTD are currently being assimilated operationally in the National Centers for Environmental Prediction (NCEP) Rapid Update Cycle (RUC) analysis-forecast system (Gutman 2005, personal communication, Gutman et al, 2004, Benjamin et al, 2004).

3. REGIONAL ANALYSIS AND FORECAST SYSTEM

The CMC regional analysis and forecast system produces analyses every 6h based on a 3D-Var assimilation of observations from radiosondes, surface synoptic stations, aircraft, satellites (winds and radiances), and the US wind profiler network. The forecast model is the regional version of the Canadian Global Environmental Multiscale (GEM) model (Coté et al, 1998). The regional GEM (GEM-REG) has 58 levels compared to 28 for the global version (GEM-GLB) and a much higher resolution (~15 km) over North America compared to GEM-GLB (~100 km). The GEM-REG also has different schemes for surface processes and deep convection than those of GEM-GLB. Details of the GEM-REG model can be found in Mailhot et al (2005).

Discrete 12-hour regional assimilation cycles with a 6h analysis interval are run twice daily at 00 and 12 UTC. Six-hour forecasts of the GEM-REG provide the first-guess fields for each of the 2 regional 3D-Var analyses. The first 6h forecast of each cycle is initialized with an analysis from the continuous 6-hour global (4D-Var, GEM-GLB) assimilation system. Forecasts up to 48 hours are run from the second regional analysis at the end of each cycle, at 12 and 00 UTC, to provide guidance for domestic aviation and 2-day public forecasts. Longer range forecasts beyond 48h are obtained from the GEM-GLB model initialized with 4D-Var analyses of the global data assimilation system.

The 6h first-guess forecasts (trials) from the CMC operational regional and global data assimilation systems are used in the monitoring of NRT GPS observations, as described in Section 4.

4. DATA MONITORING

The ground-based GPS observations monitored by MRB are those designated for assimilation, namely ZTD and GPS Met from the NOAA/FSL network as described in Section 2. Monitoring of the observations (O) is done in near real time by comparison against first-guess values (P) from the CMC operational regional and global data assimilation systems. The results presented here are for comparisons with P from the regional system trial fields. Results with global trial fields are similar. The focus will be on ZTD observations.

Monitoring results are available online at http://collaboration.cmc.ec.gc.ca/science/arma/sat/gb_gps/monitoring_html/gps_monitoring.htm.

4.1 *Method*

Every 6 hours, all available 30-minute observations are collected from the NOAA/FSL network for the 6h assimilation window centred at analysis times of 00, 06, 12 and 18 UTC. Observations (O) closest to the analysis times are compared to first-guess values (P) taken from the latest trial fields interpolated to the observation locations. The first-guess ZTD (ZTD_P) is obtained from trial surface pressure (P_S) and vertical profiles of temperature (T) and specific humidity (Q) as follows:

$$ZTD_P = f_1(\varphi, H)\, P_0 + (P_S - P_T)\sum_{\eta=0}^{\eta=1} f_{QT}(Q_\eta, T_\eta)\,\Delta\eta_\eta + \Delta ZWD_{DZ} \quad (2)$$

where η is the GEM P_S-based eta vertical coordinate (0 at model top and 1 at the surface), P_T is the model top pressure (10 hPa), and $\Delta\eta$ is the difference in η between adjacent model levels (which varies with η). The first term is the zenith hydrostatic delay (ZHD) component, i.e., the component of ZTD due to integrated air density (P_S). Here P_0 is the trial P_S adjusted hydrostatically to the GPS antenna height. The second term is the trial zenith wet delay (ZWD) component of ZTD (due to PW). The function f_{QT} is essentially the wet refractivity due to water vapour (Q). The last term is the correction of ZWD to the antenna height, where DZ refers to the height difference ΔZ between trial surface and the antenna.

The method for DZ correction is similar to that proposed by Higgins (1999). The mean wet refractivity N_W of the DZ layer is estimated from layer mean values of pressure, T and Q. The layer mean pressure is the mean of P_S and P_0 while layer mean T and Q are obtained by assuming fixed lapse rates of T and Q between trial surface and antenna height. The DZ correction to ZWD is then simply

$$\Delta ZWD_{DZ} = \overline{N}_W\, \Delta Z \quad (3)$$

For sites in the NOAA/FSL network and GEM-REG trials, $|\Delta Z|$ is < 100 m for ~85% of the sites.

The antenna heights used to compute ΔZ for terms 1 and 3 of (2) are taken from a site information file provided by NOAA/ESRL which is updated periodically to reflect changes in the network. Antenna height errors will create bias errors in ZTD_P. For example, a 10 m error in antenna height gives a ~3 mm error in ZTD_P. The antenna heights in the file are based on precise positions obtained from network GPS data processing, converted to height above mean sea level (MSL), so any error should be minimal (< 1 m).

The O-P differences for ZTD and GPS Met are calculated every 6 hours for each site and appended to monthly data files. Monthly values of mean (bias) and SD of O-P for each site and for the network as a whole are then updated. For monitoring GPS Met Ps, it is assumed that the barometer is at the same height as the GPS antenna, and the trial P_S is adjusted hydrostatically to that height, as done to obtain P_0 for computation of ZTD_P in (2). Observed Ts is compared to trial surface T (at η=1) extrapolated to antenna height with an assumed lapse rate of −0.65 K km^{-1}. Observed RH is converted to dewpoint depression DPD (the moisture variable for data assimilation) for direct comparison with trial surface DPD.

4.2 *Monitoring Results*

The network-wide mean and standard deviation (SD) of ZTD O-P at 6h intervals (analysis times) for August 2005 are shown in Figure 2. The network mean O-P is on average close to zero while the average SD is ~25 mm. The mean varies little with month (not shown), while the SD is considerably lower in winter (~10 mm).

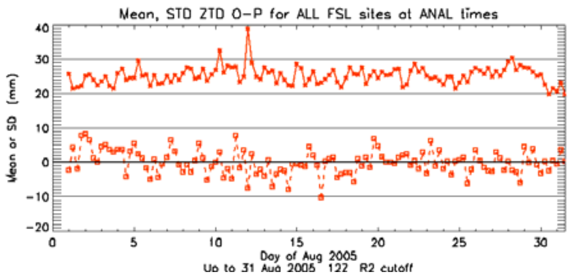

Figure 2: Time series of mean and SD ZTD O-P (mm) for FSL network at 6-h intervals for August 2005. The lower series (dashes with boxes) is the mean series.

Plotted in Figure 3 are monthly SD of ZTD O-P for each site for June 2005. The SD ranges from 10-35 mm with higher values in the eastern US, where average

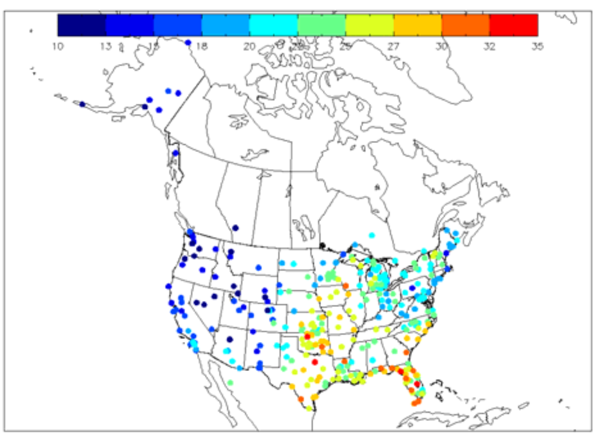
Figure 3: SD of ZTD O-P (mm) for June 2005

moisture (PW) is higher. This dependence of the SD on PW is clearly evident in Figure 4, a plot of site SD ZTD O-P as a function of site mean PW for the same month (June 2005). The combined effect of random errors in observed and first-guess ZTD increases with increasing PW (Deblonde et al, 2005).

The 11-month (Nov 2004 to Sep 2005) mean ZTD O-P for each site are shown in Fig. 5. The bias magnitude is < 10 mm for 95% of the sites. Higher biases (at 19 sites) are in the 10−15 mm range with no clear dependence on geographical region. Biases of the same order as the SD, pose a problem for data assimilation.

Different bias errors for observations (O) and first-guess values (P) contribute to O-P biases. A cause of bias errors in ZTD estimates (O) is specification of imprecise a-priori antenna heights in the geodetic GPS data processing. Satellite position (orbit) errors are typically random and transient. While such errors can cause a temporary network-wide bias, they have little impact on site O-P biases averaged over long periods.

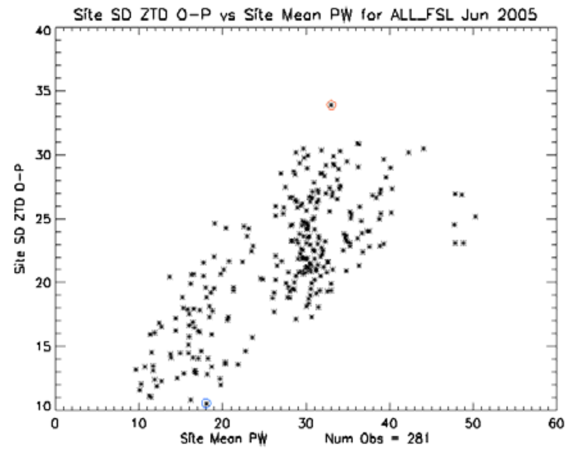

Figure 4: Site SD of ZTD O-P (mm) as a function of site mean PW (mm) for June 2005

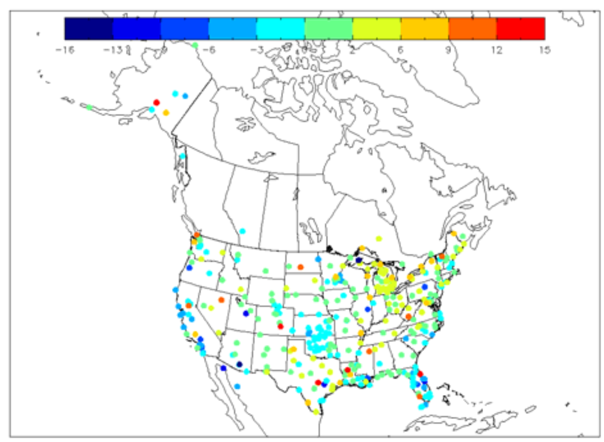
Figure 5: Average ZTD O-P bias (mm) for Nov 2004 to Sep 2005 (11 months)

First-guess (P) bias errors are due to systematic errors in forecast fields (Ps, T, Q), horizontal interpolation from model grid points to observation location, and in the DZ correction of trial values to observation (antenna) heights. Most NWP models have biases that vary with location, season and time of day.

The site O-P biases have constant and variable components. The variable component is responsible for variability in bias at time scales of weeks to seasons. Diurnal variability is also evident at some locations. The amplitude of the variability can be a significant fraction of the total bias. An example of high seasonal variability is seen in Figure 6, a plot of monthly ZTD O-P bias for site Talkeetna, Alaska (TLKA2), which varies from ~4 mm in the winter to > 20 mm in the summer. It is assumed that the variable bias component is related to variability in the forecast and actual atmospheric state.

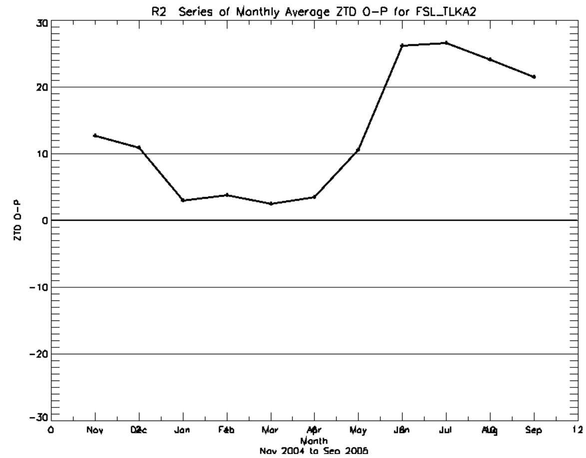

Figure 6: Monthly mean ZTD O-P (mm) for site TLKA2 for period of November 2004 to September 2005

The constant component is likely related to antenna height issues. The 11-month site mean ZTD O-P values plotted in Fig. 5 reflect a constant component of site biases, as the variable atmosphere-related component is averaged out. Large biases (> 10 mm) are associated with a significant constant component of bias error. An error in a-priori antenna height for the site Bismark, ND (BSMK) was recently identified by NOAA/ESRL, consistent with the relatively high average ZTD O-P bias for the site (12.6 mm). The possibility of similar errors at other sites is being investigated.

5. ASSIMILATION OF GPS OBSERVATIONS

1D-Var experiments with synthetic GPS ZTD observations show that the main impact of GPS data assimilation is on the analysis of humidity in the lower troposphere (below 400 hPa). An exception is assimilation under very dry (low PW) conditions where the impact is mainly on surface pressure. Changes in the analysis of humidity have a potentially significant impact on forecasts of clouds and precipitation. Indirect effects on other forecast elements such as temperature and winds are expected through the physics of the GEM model (e.g., radiation, convection, thermodynamic processes).

Assimilation of GPS Met observations has obvious impacts on analyses of surface pressure and near-surface humidity and temperature. There is also some evidence to suggest that the distribution of moisture analysis increments in the vertical from ZTD assimilation is improved when GPS Met surface humidity observations are assimilated at the same time (De Pondeca and Zou, 2001).

Positive impacts from assimilation of NOAA/FSL GPS observations are expected to be most evident in a 4D-Var assimilation system combined with a high-resolution forecast model. As such a system is not yet available at CMC, a modified version of the current 3D-Var regional system described in Section 3 is used for preliminary tests. The normal 3D-Var assimilations are replaced by 3D-Var FGAT (First Guess at Appropriate Time) to make better use of the 30-minute GPS observations. Analyses from the 4D-Var global assimilation system (without GPS observations) provide initial conditions for the first forecast (trial) of the regional cycles. Ideally, these global cycle analyses should include GPS observations as well.

No thinning or bias correction of the GPS observations are performed for the tests. The distance between some sites in the NOAA/FSL network is very small. In addition, the sites report at 30-minute intervals while the FGAT time-step for O-P computations is set at 45 minutes. The preliminary test results suggest that these issues need to be addressed. A routine has recently been prepared to thin the GPS observations in both time and space. A minimum separation distance is specified and closely-spaced sites are filtered with a scoring system. Other options include combining (averaging) clusters of observations into single “super-observations” to achieve a more even spatial distribution.

Two bias correction schemes under consideration are based on the running-mean and regression approaches. In the running-mean approach, the mean O-P at each site over a fixed period of time is determined and applied as a bias correction to the observations prior to assimilation. The regression technique, used for TOVS radiances, attempts to predict the bias through multiple linear regression (MLR) with O-P as predictand and trial elements such as layer thicknesses as predictors. While the regression technique may prove effective in removing the variable bias component for GPS observations, it will fail to remove any constant component unless regressions are done on a per-site basis. The running mean method will fail to remove variations in bias at time scales much lower than the averaging interval and will be ineffective during periods of rapid transition to a different bias level due to inherent time-lag. Some combination of the two methods may be preferable.

The assimilation test results are not presented here, as they are based on early experiments with incomplete pre-processing of GPS observations and sub-optimal assimilation configurations. Further tuning of the test system configuration is planned along with assimilations of thinned and bias-corrected GPS data.

Proposed changes to the CMC data assimilation systems in the near future will provide better operational configurations for assimilation of GPS observations, namely:

- new global data assimilation and forecast system with 4D-Var and a new mesoglobal version of the GEM model (higher global resolution of ~35 km and more vertical levels (58) with similar physics to GEM-REG)
- 3D-Var FGAT or 4D-Var incremental analysis in the regional assimilation system
- higher resolution GEM-REG (~10 km over North America)

6. SUMMARY

Monitoring of NRT ground-based GPS observations from the NOAA/FSL GPS network has revealed some issues which must be addressed before the data can be assimilated. Biases between observations and first-guess values have been identified and methods for bias correction proposed. Thinning of the observations is also recommended.

Results of experiments with a modified version of the CMC regional assimilation and forecast system are not presented here, as they were performed mainly for test purposes, with sub-optimal system configurations and no pre-processing (thinning, bias correction) of GPS observations. It is expected that GPS observations will be a valuable source of moisture information in the high-resolution assimilation-forecast systems to be implemented soon at CMC.

Other uses for GPS observations include NWP model validation. Radiosonde data, commonly used for this purpose, are only available twice a day from sites that are often widely separated. GPS observations can provide integrated moisture information at other times and locations for model validation purposes.

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