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Assimilation Experiments with Ground-based GPS Observations in the Canadian Regional Deterministic Prediction System

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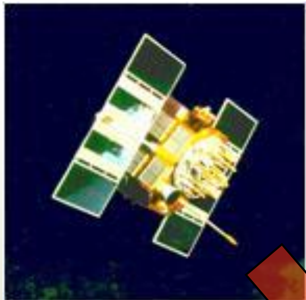
Outline

- Ground-based GPS technology
- The NOAA GB-GPS Network
- GB-GPS data monitoring
- Assimilation of GB-GPS data in the EC RDPS
- Assimilation experiment results
- Summary
- Future Work

Sensing Atmospheric Water Vapour with Ground-based GPS Receivers



zenith

Atmosphere

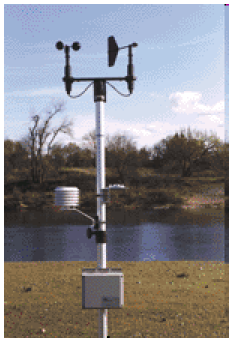
map to zenith

Refractivity N induces delay in signal reception

$$N = k_1 \frac{P}{T} + (k_2 - k_1)\frac{e}{T} + k_3 \frac{e}{T^2}$$

- **density (*P*/*T*)**
- **water vapor (*e*) dipole moment**

GPS Receiver
high accuracy, dual frequency



Surface Weather Station

Zenith Tropospheric Delay
ZTD = F(Ps,PW)

+

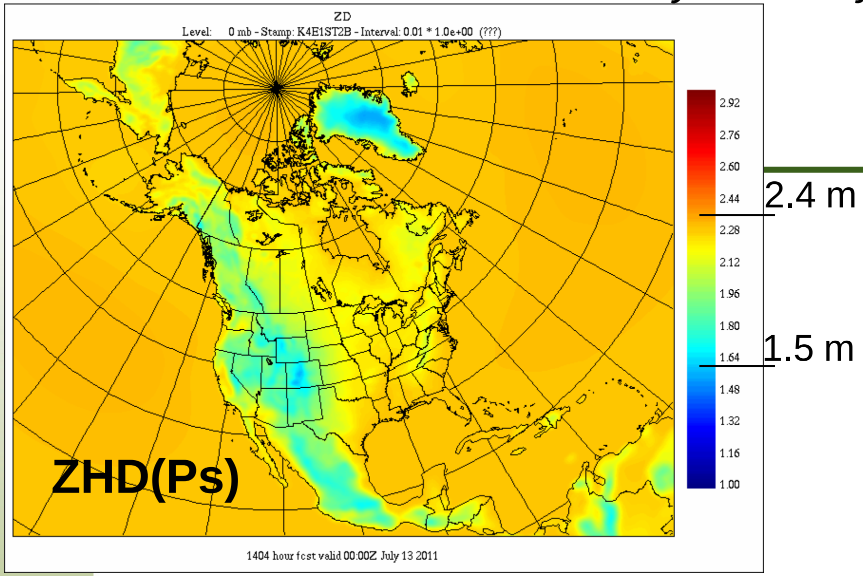
Pressure (Ps)
Temperature
RH

Precipitable Water (PW)

$$ZTD \equiv 10^{-6} \int_{z=sfc}^{toa} N\,dz$$

ZTD is estimated from raw GPS receiver data with geodetic processing software (e.g. GAMIT) designed for precise positioning applications

Mean NWP 6h forecast fields 15 May – 13 July 2011



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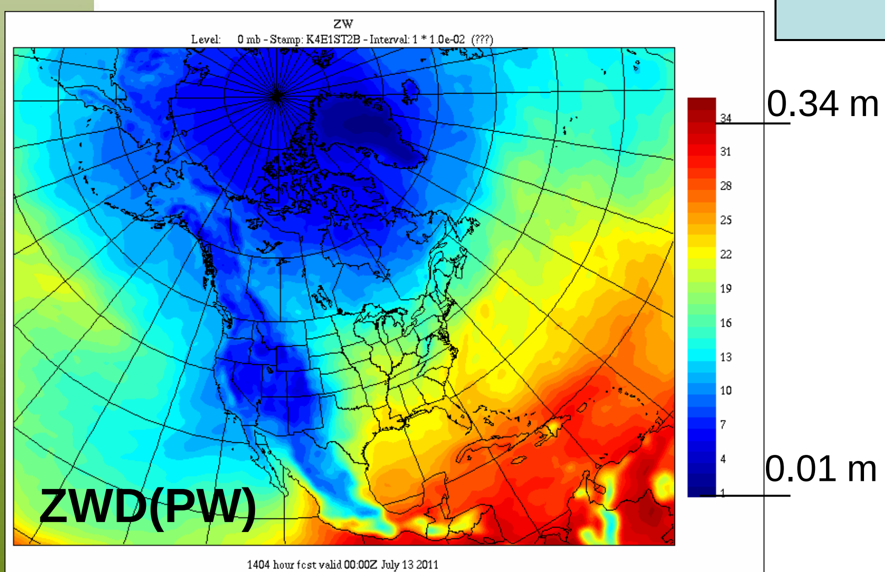
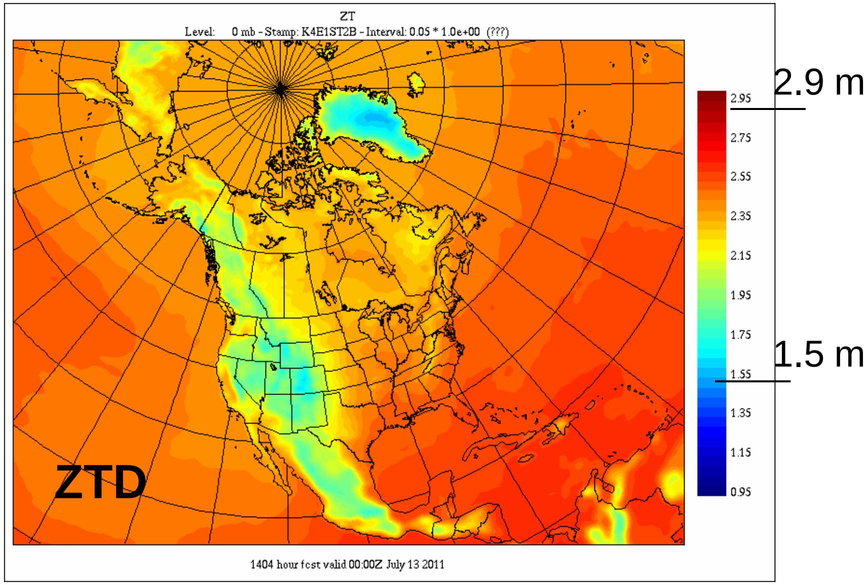


Components of ZTD

ZTD = ZHD(Ps) + ZWD(PW)



ZHD (mm) ≈ 2.4 · Ps (hPa)

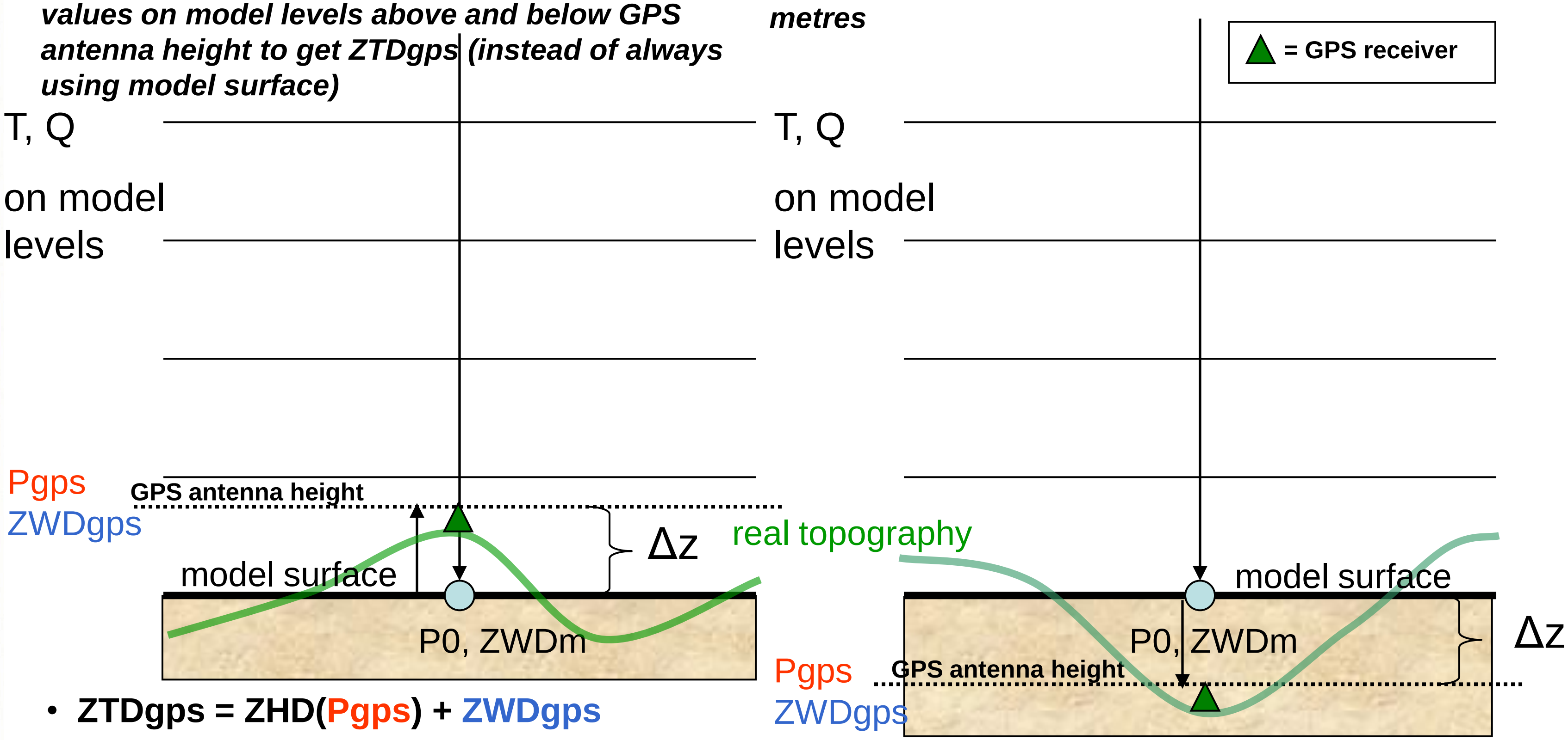
ZWD (mm) ≈ 6 · PW (mm)

Forward Model for ZTD at GPS antenna height

Computing ZTD from NWP (model) fields

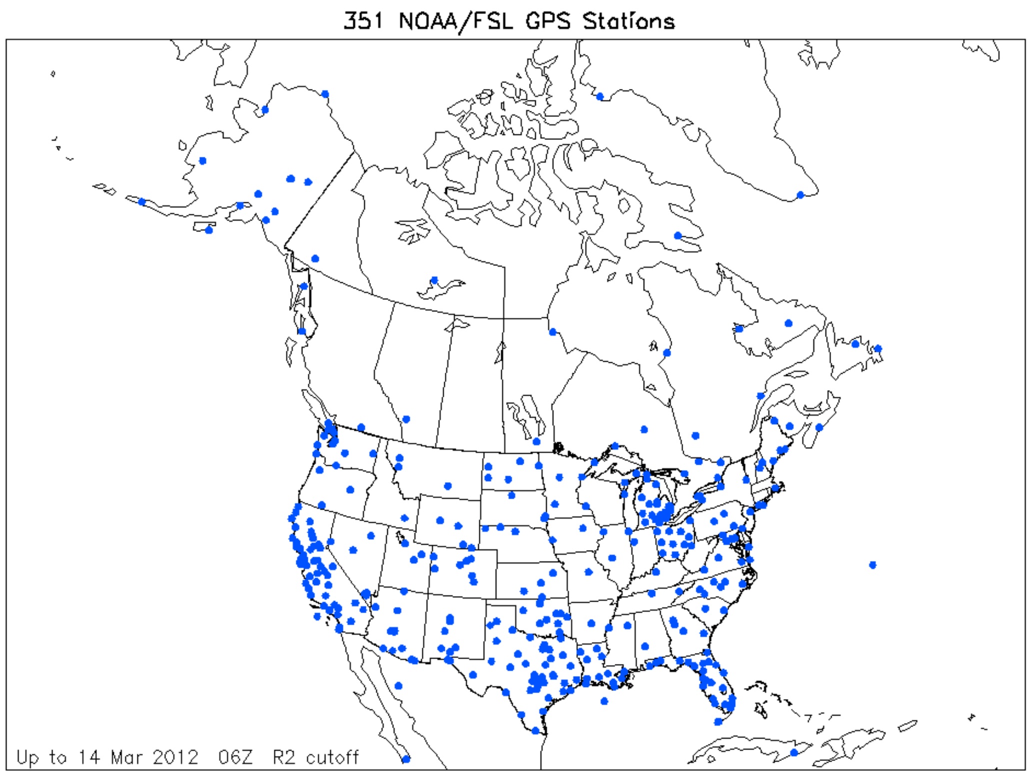
when Δz > 0, "interpolation" option exists to use values on model levels above and below GPS antenna height to get ZTDgps (instead of always using model surface)

For assimilation, max abs(Δz) is set to 1000 metres



- **ZTDgps = ZHD(Pgps) + ZWDgps**
- **Pgps** = F(P0, Tv_{mean}, Δz) [hydrostatic adjustment]
- **ZWDgps** = **ZWDm**(P0,∫[Q/T]) + **ΔZWD**
  - **ΔZWD** = − *N*w · Δz where *N*w = Function of mean (P, T, Q) in Δz layer.

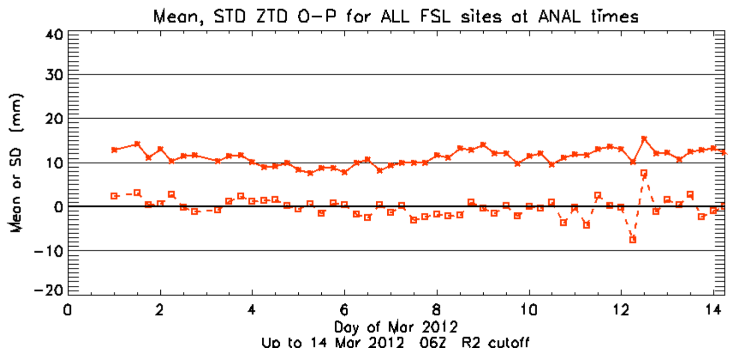
The NOAA Ground-based GPS Network

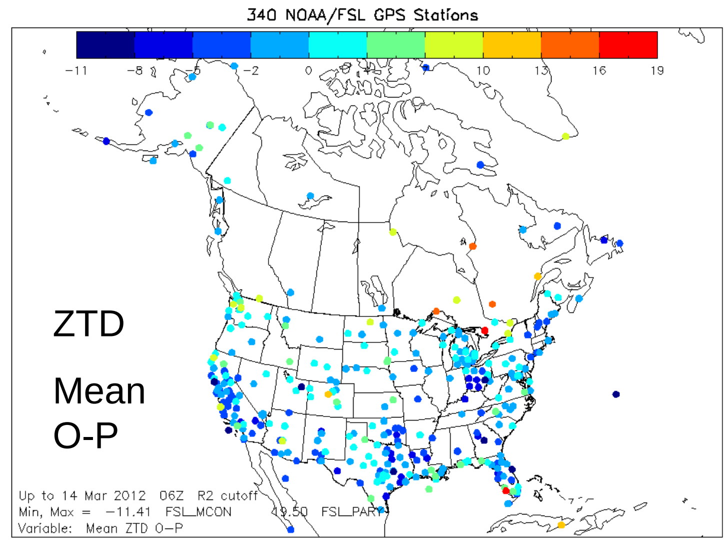


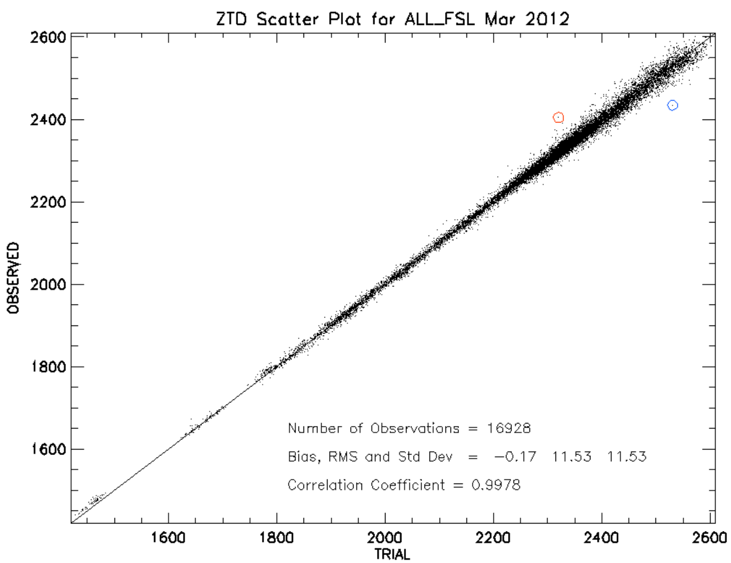
- Network started in 1994 by NOAA/FSL (now ESRL) as a research demonstration network
- **All-weather** GPS **ZTD**, PW and **surface met** data (Ps, Ts, RHs) available every 30 minutes
- High data reliability and accuracy that improves with time
- GPS PW data are assimilated operationally in NCEP regional models
- More existing GPS sites in Canada could be added (e.g. provincial GPS receiver networks)

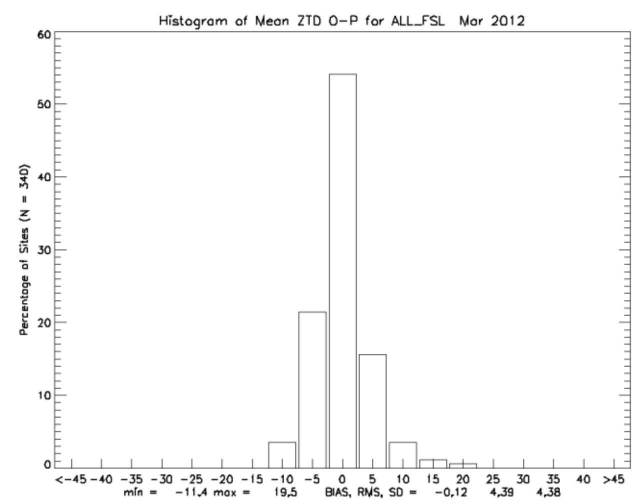
Near-Real-Time GB-GPS Data Monitoring at EC

Comparison of Obs (O) with NWP 6h forecasts (P)





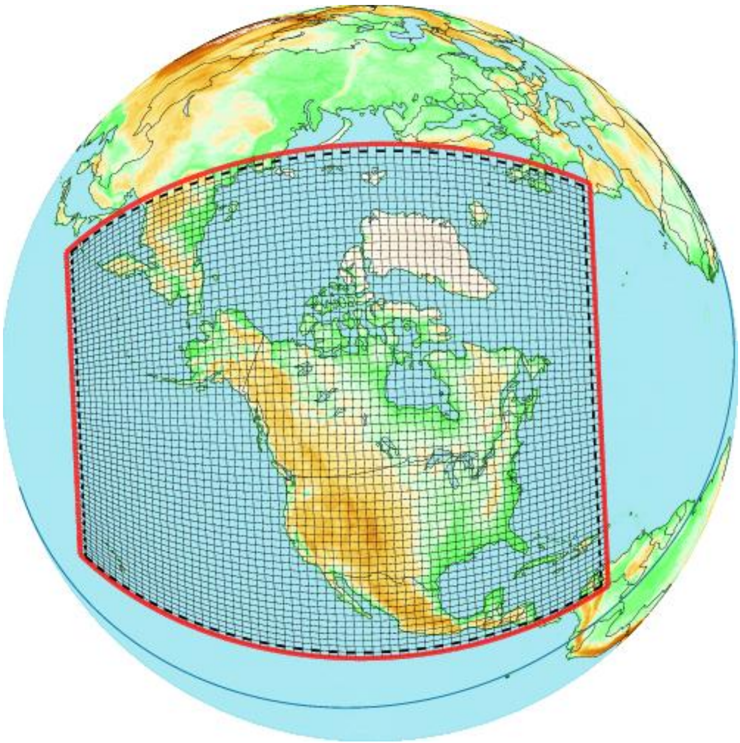




Assimilation of GB-GPS data

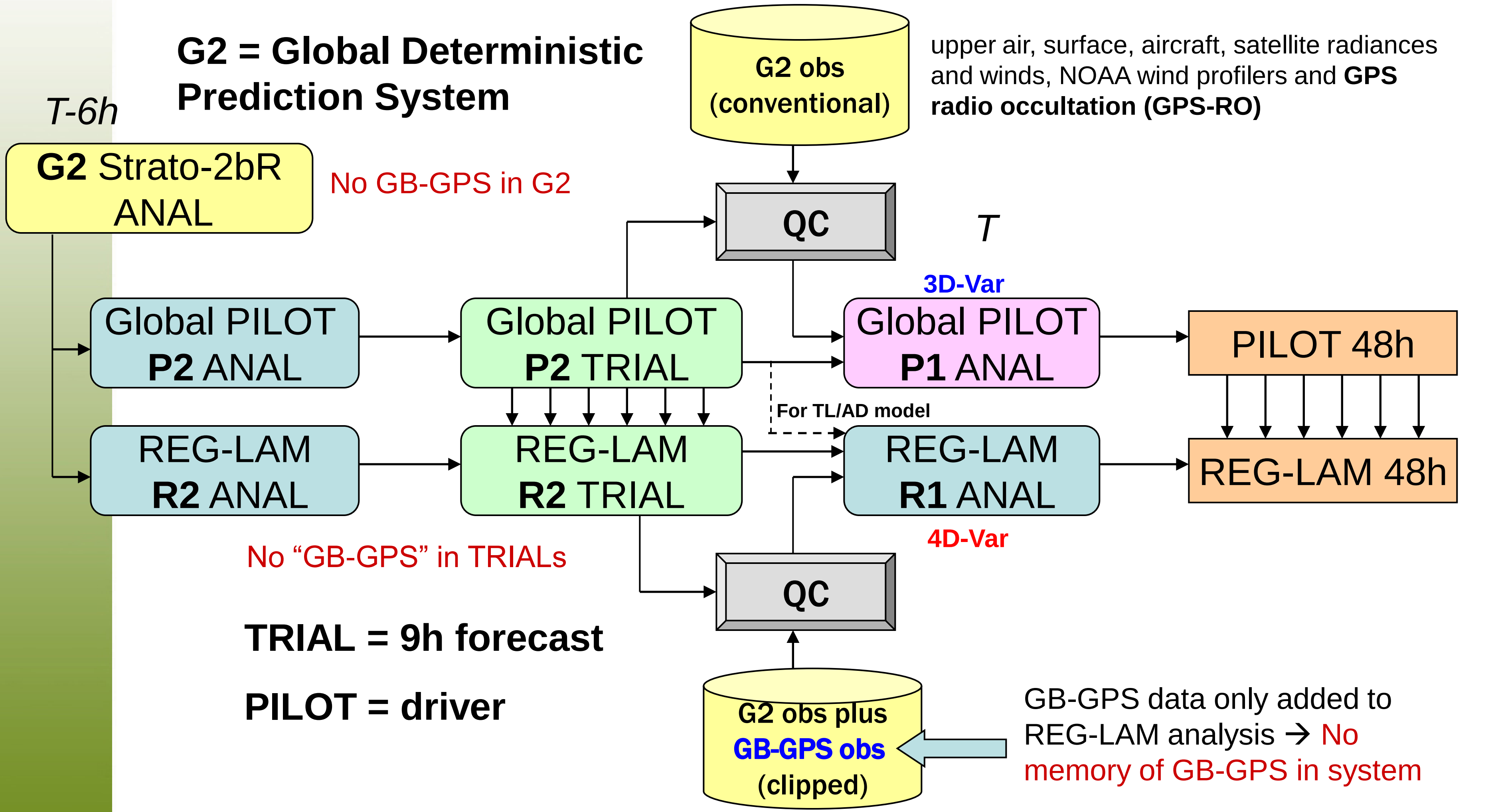
- Assimilation of GPS **ZTD** from the NOAA GB-GPS network is tested in the EC **R**egional **D**eterministic **P**rediction **S**ystem (RDPS)
- Collocated GB-GPS surface met data (Ps, Ts, RHs) are also assimilated unless GPS site is within 50 km of reporting surface or upper air site (avoids potential data duplication)
- Quality control of GB-GPS data, performed before assimilation using NWP forecast (first guess = fg), includes:
  - rejection of data based on magnitude of obs-fg (outlier removal)
  - rejection of data based on site obs-fg statistics (e.g., high mean or StdDev, high percentage of bad data, insufficient number of reports to determine statistics, etc.)
  - rejection of ZTD data with high “formal error” > 15 mm
- Mean obs-fg ZTD statistics reveal site-specific biases that are removed before assimilation with a dynamic (10-day running-mean) bias correction system
- Spatial (50 km) and temporal thinning are applied to the GB-GPS data (1 observation per site per 6h analysis window, closest to central time)

Regional Deterministic Prediction System (RDPS)



- Regional GEM Limited Area Model (REG-LAM) – 15 km, 80 hybrid levels (L), top at 0.1hPa
- Initialized every 6h with 4D-Var analysis from 33km 80L **Global Deterministic Prediction System** (GDPS)
- Driving of REG-LAM forecasts from 55 km 80L global model (provides boundary conditions)
- 3D-Var OPS (4D-Var tests) REG-LAM analysis, with same observations as GDPS assimilated (but clipped), provides initial conditions for 48h forecast
- *In development: 10 km REG-LAM, 33 km global driver, 4D-Var, (25 km GDPS)*

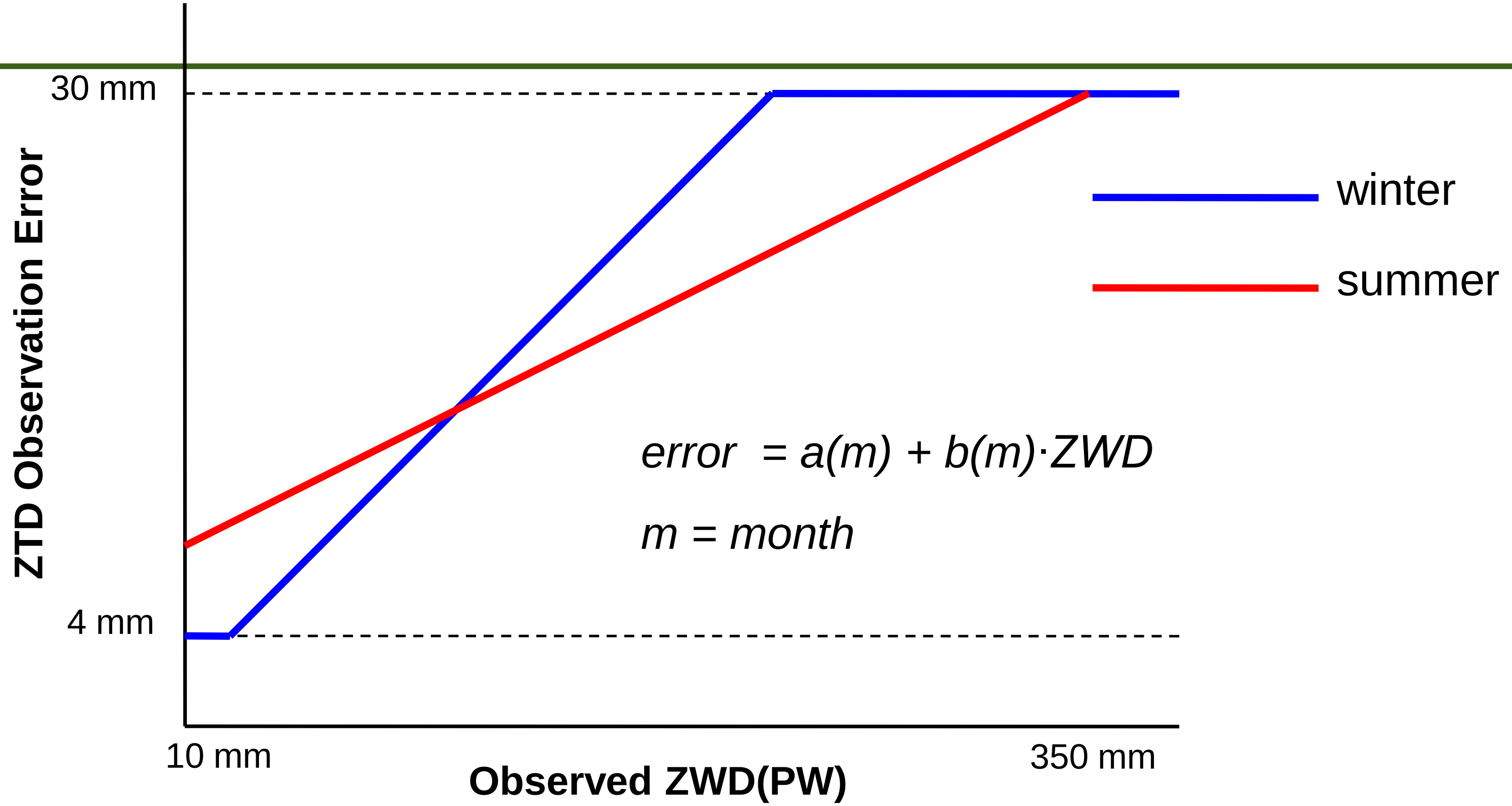
Regional Deterministic Prediction System (RDPS)



Assimilation of GB-GPS data

- Assimilation in RDPS assimilation tests with GB-GPS data were done with soon-to-be-operational 4-dimensional variational analysis system (**4D-Var**)
- GPS ZTD is a **single observation** dependent on vertically integrated quantities, in contrast with true "profile" data from radiosondes, GPS-RO, wind profilers and aircraft. As a result, 3D analysis increments in control variables from ZTD assimilation may not always be optimal.
- Impact of ZTD assimilation on the analysis depends on
  - Magnitude of observed minus trial (first-guess) ZTD difference
  - Jacobian (sensitivity) of ZTD with respect to analysis control variables (surface pressure P0, temperature T(z) and log of specific humidity LQ(z))
  - First-guess (6h forecast) errors for control variables and their covariances (as specified in background error covariance matrix). Note that absolute humidity (Q) error increases with increasing Q due to LQ error specification, which means forecast ZTD error increases with PW.
  - Observation error specified for ZTD (increases with observed ZWD (PW)).

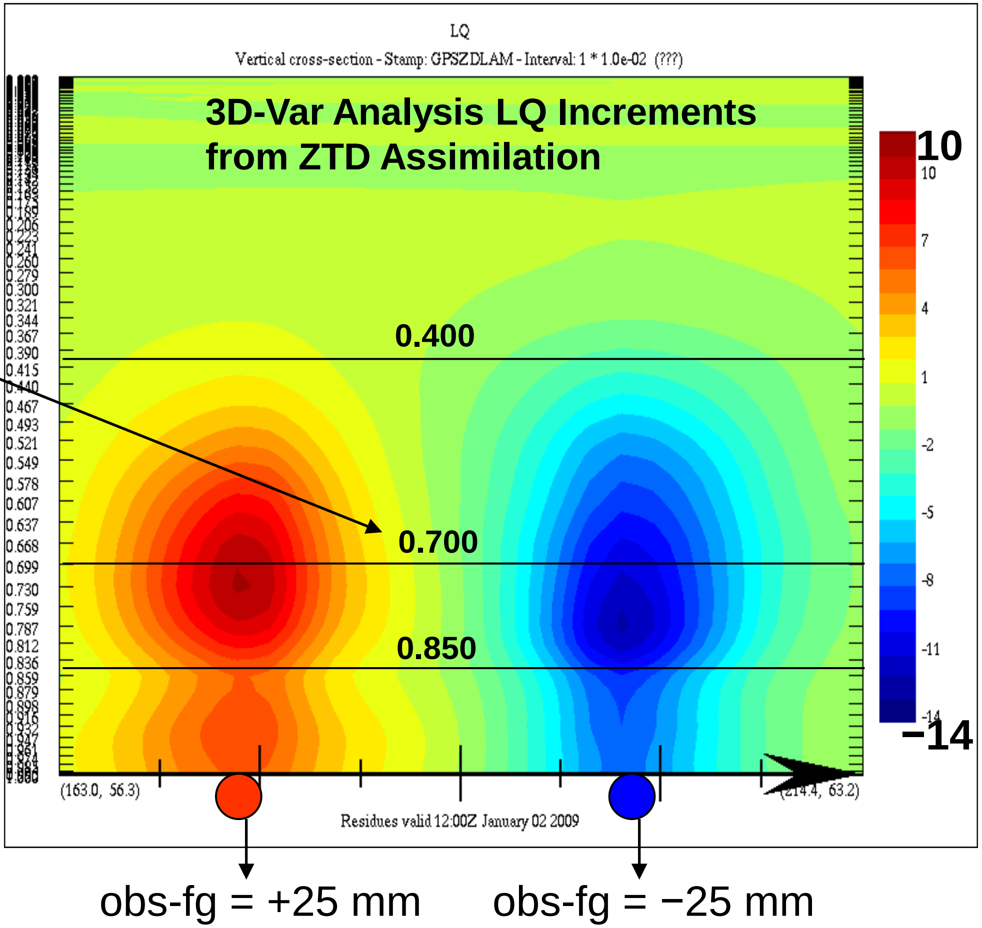
GPS ZTD Observation Error Specification



- Based on linear regression of site monthly ZTD StdDev(obs-F6h) with site mean monthly ZWD(PW); assume ZTD error = StdDev(obs-F6h)
- In analysis, tends to give similar weights for background (F6h) and observation (obs) over wide range of PW, as errors for both F6h and obs ZTD increase as PW increases

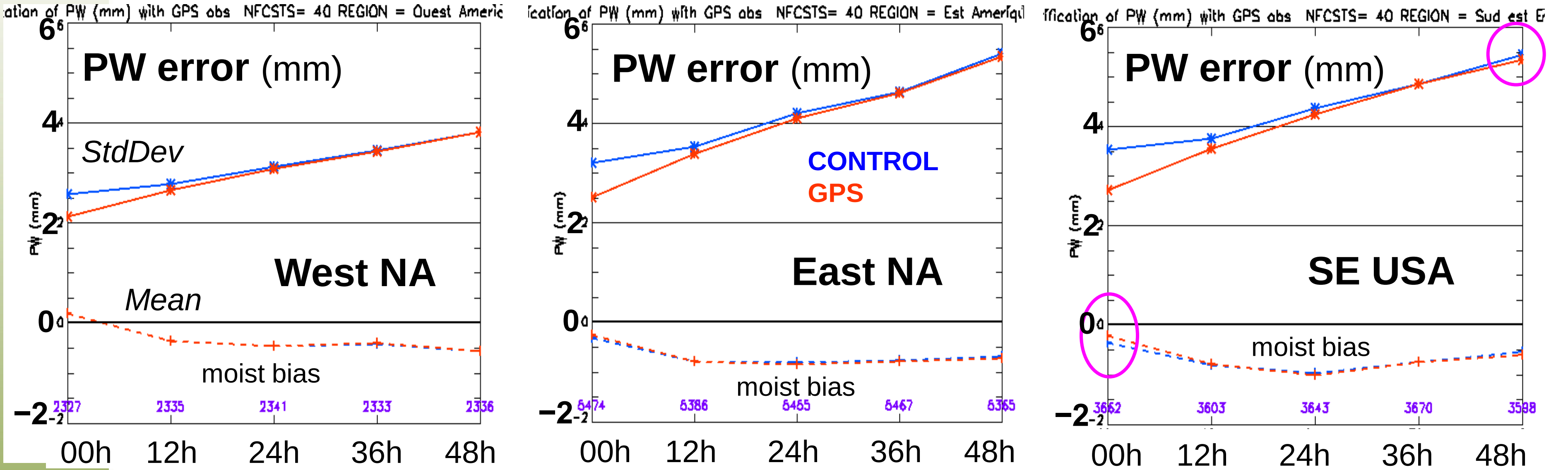
Assimilation of GB-GPS Data

- Assimilation of GPS ZTD produces LQ increments in the lower troposphere (below 400 hPa), with little impact on T or P0. LQ increments are max around 700-800 hPa level on average.
- LQ increments are generally small compared to those from conventional observations (e.g. radiosonde humidity).
- P0 analysis increments on the order of 1-2 hPa can occur when trial is very dry (PW < 2 mm)



Assimilation Experiment Results

4D-Var RDPS, summer 2011, 40 dates (00Z and 12Z only)



Verification of 48h RDPS Forecast PW using GB-GPS PW observations

- 25-30% reduction in analysis PW (StdDev) error with smaller reductions at 12h and 24h; generally little impact on StdDev error beyond 24h or model moist bias error
- Small impact of GB-GPS data seen at 48h for SE USA region
- Slight drying in SE USA region at 00h in **GPS** reduces analysis (00h) moist bias with associated reduction in 00-24h precipitation for Gulf States (not shown)

Assimilation Experiment Results

- Other forecast verifications done include
  - verification of wind, temperature, geopotential height (GZ) and dewpoint depression against **radiosonde observations**
  - verification of 24h **precipitation** accumulations against North American rain gauge networks (SYNO and SHEF)
  - verification with North American surface weather reports (temperature, dewpoint depression, cloud cover, winds)
- Results from these verifications reveal small mixed impact of the GB-GPS data (not shown). Small positive impact on GZ for SE USA region.
- Benefit of GB-GPS data may be masked by cloud and precipitation “spin-up” effects in the REG-LAM forecasts which adversely affect the quality of the short range forecast (0-6h); also, choice of analysis humidity control variable (LQ) may not be best one (could be changed in the future).
- Experiments done for **winter** periods show smaller and more short-lived (< 6h) impact of GB-GPS data assimilation. This is due to fact that average PW is much lower in winter. Thus forecast errors in specific humidity are lower, limiting the impact of observations.

Summary

- Ground-based GPS data (ZTD and surface met) from the NOAA GB-GPS network have been assimilated in experiments with the Environment Canada Regional Deterministic Prediction System (EC RDPS)
- The GB-GPS data have a positive impact on RDPS precipitable water (PW) analyses and 00-24h forecasts (when GB-GPS PW observations are used for verification); conventional forecast verifications reveal little overall impact of GB-GPS.
- In earlier GB-GPS data impact tests, positive impacts were more evident when examining individual forecasts (case studies).
- GB-GPS PW observations are useful for forecast PW verification (even if GB-GPS data not assimilated)
- Conservative assimilation strategy in the experiments combined with limited sample size (40 dates 00Z and 12Z only, summer 2011) may help to explain observed minimal impact of GB-GPS data.
  - only 1 observation per site per 4D-Var analysis (when up to 12 available)
  - no “memory” of GB-GPS data in RDPS (data not in driving GDPS)

Future work

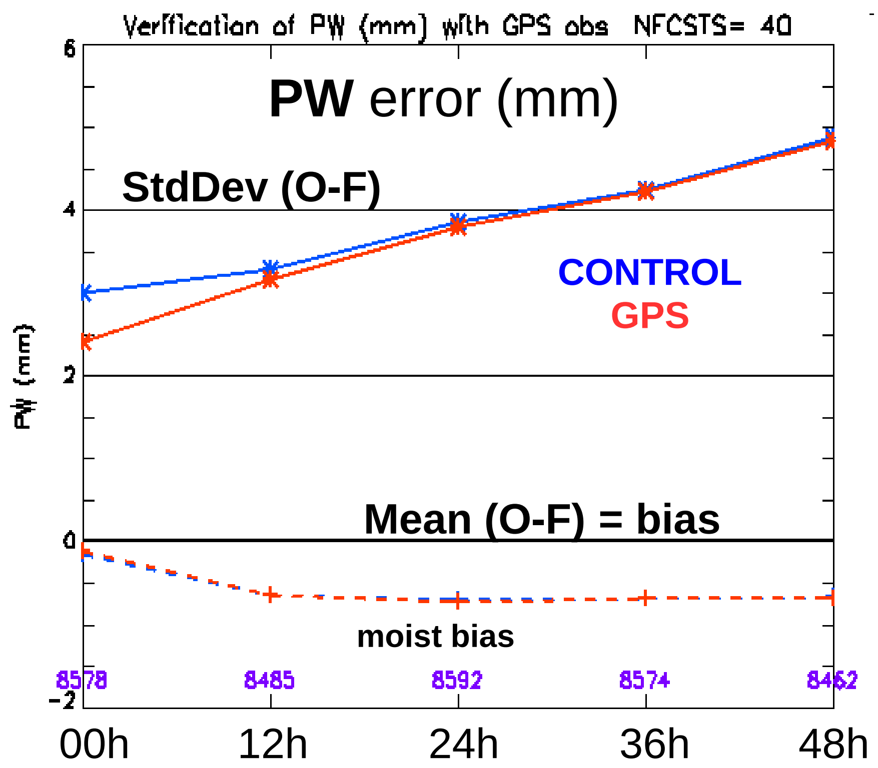
- Test assimilation of GB-GPS data in new 25 km version of the EC global system (GDPS) with continuous (Δt=6h) analysis cycle where "memory" of assimilated GB-GPS data is retained (15 km GDPS in research)
- Test assimilation of time-series GB-GPS data, accounting for serial observation error correlations (e.g. ECMWF method).
- Test impact of GB-GPS data by removing conventional moisture data over North America (e.g. radiosondes).
- Re-evaluate ZTD observation error specification. Errors as high as 30 mm may be too high considering that actual formal "instrument" errors are as low as 4 mm.
- Examine ZTD bias correction strategy:
  - static vs dynamic, optimal averaging period, etc…
  - better understand source of biases and remove where possible (collaboration with NOAA/ESRL)
  - discrimination of model vs observation bias

Thank You

Supplemental Slides

Assimilation Experiment Results

4D-Var, 3D data thinning for GB-GPS, summer 2011 (latest)

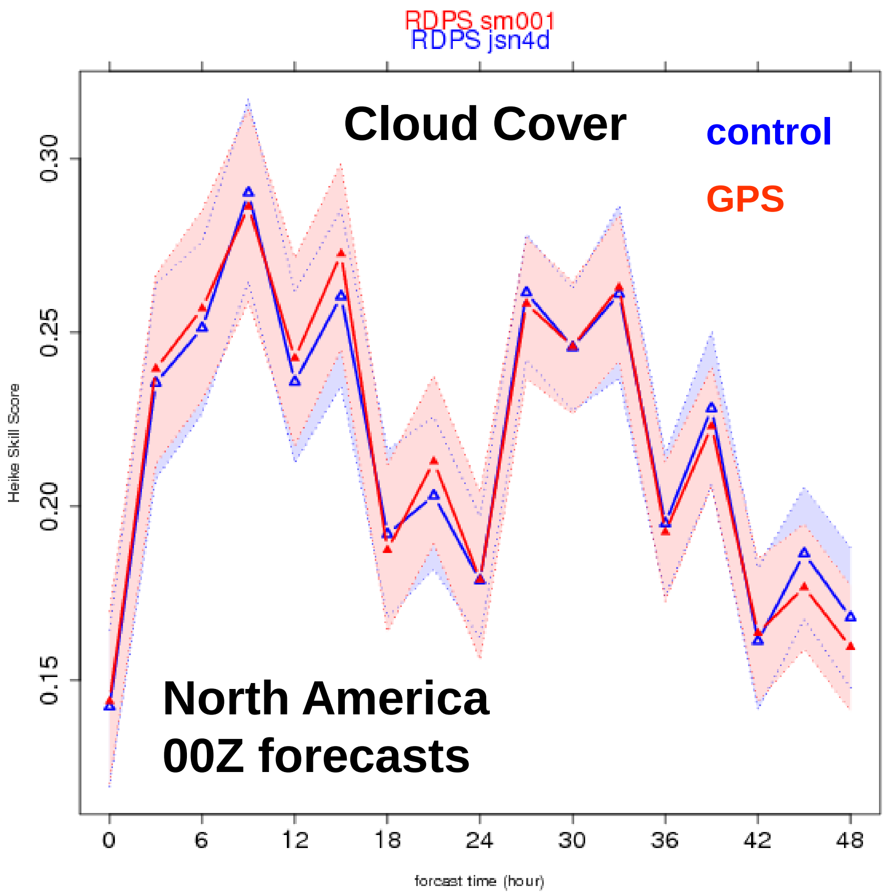


Verification of 00-48h RDPS Forecast PW using GB-GPS PW observations

- **PW** forecast error is reduced in experiment with GB-**GPS** (at 00h, 12h and 24h)
- Little impact of GB-GPS on moist forecast (model) bias
- Results by region (next slide) show some differences.

Assimilation Experiment Results

4D-Var, 3D data thinning for GB-GPS, summer 2011 (latest)



Verification of 00-48h RDPS Forecasts using North America surface observations

- Heidke Skill Score for **cloud cover** categories (clr, sct, bkn, ovc)
- **GPS** experiment shows some improvement in skill up to 24h
- Verification of other elements (temperature, dewpoint-depression) show small mixed impact overall, with some positive impact (reduced biases) noted for **GPS** at very short range (0-9h), probably from assimilation of GPS surface met data.

Assimilation Experiments with RDPS

REG-LAM Analysis	GB-GPS Thinning[1]	Periods	Number Dates	Experiment Names
3D-Var FGAT Δt =36h, 00, 12Z	4D	Summer 2008 Winter 2008-09	40 40	ml009e08 ml009h09
	3D	Summer 2008	40	ml014e08
4D-Var, Δt =12h, 00, 12Z	3D	Summer 2008	118	sm040e08[2]
4D-Var, Δt =36h, 00, 12Z	3D	Winter 2008-09	40	sm040h09
4D-Var, Δt =36h, 00, 12Z	**3D**	**Summer 2011**	**40**	**sm001e11[3]**

[1] **3D** thinning = only keep 1 observation per site (closest to central [analysis] time Ta)
4D thinning = 30-minute observations are distributed over 9 temporal bins (1 per bin) spanning Ta-3h to Ta+3h

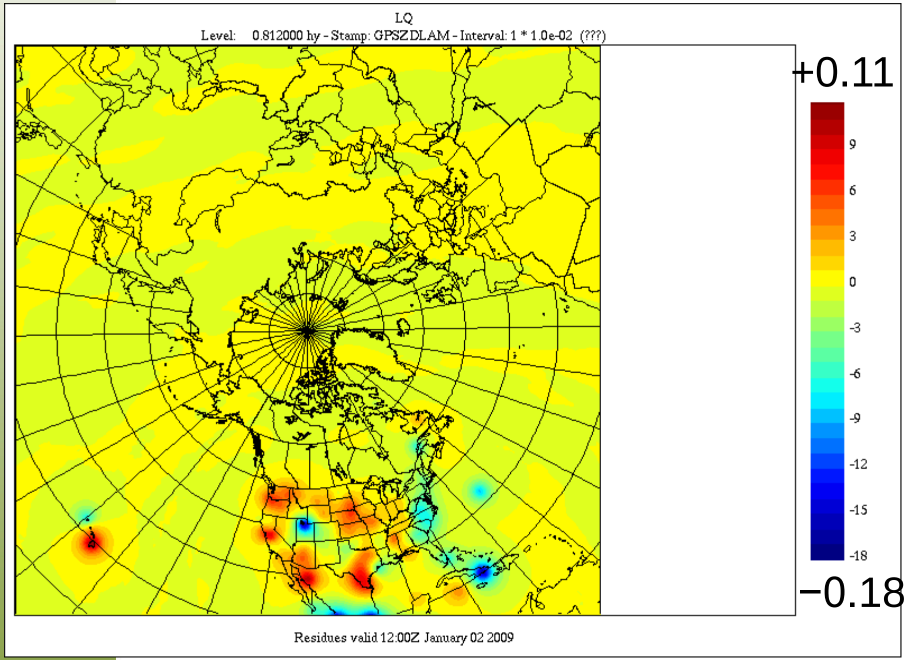
[2] introduced **blacklisting** of GP surface met data at GPS sites within 50 km of a SF/UA station

[3] **static bias correction** of GP ZTD based on obs-fg stats from **REG-LAM** trials over summer 2011 period

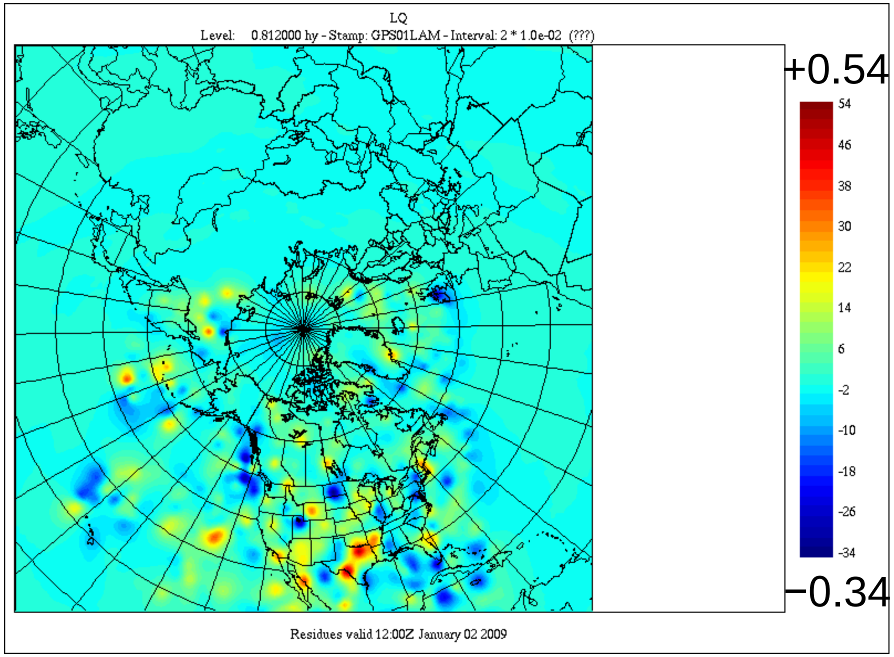
Δt = time interval between analyses

3D-Var LQ = Log(Q) Analysis Increments

From GB-GPS ZTD only



From Conventional Observations



LQ increments are small compared to those from conventional observations (e.g. radiosondes)

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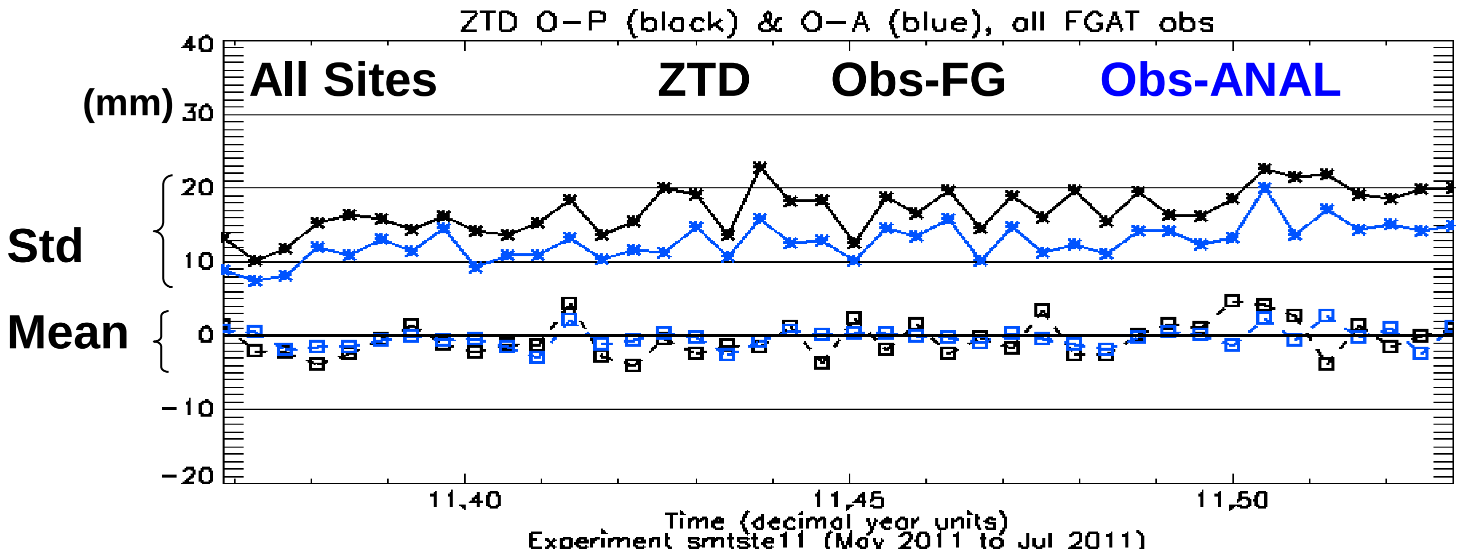
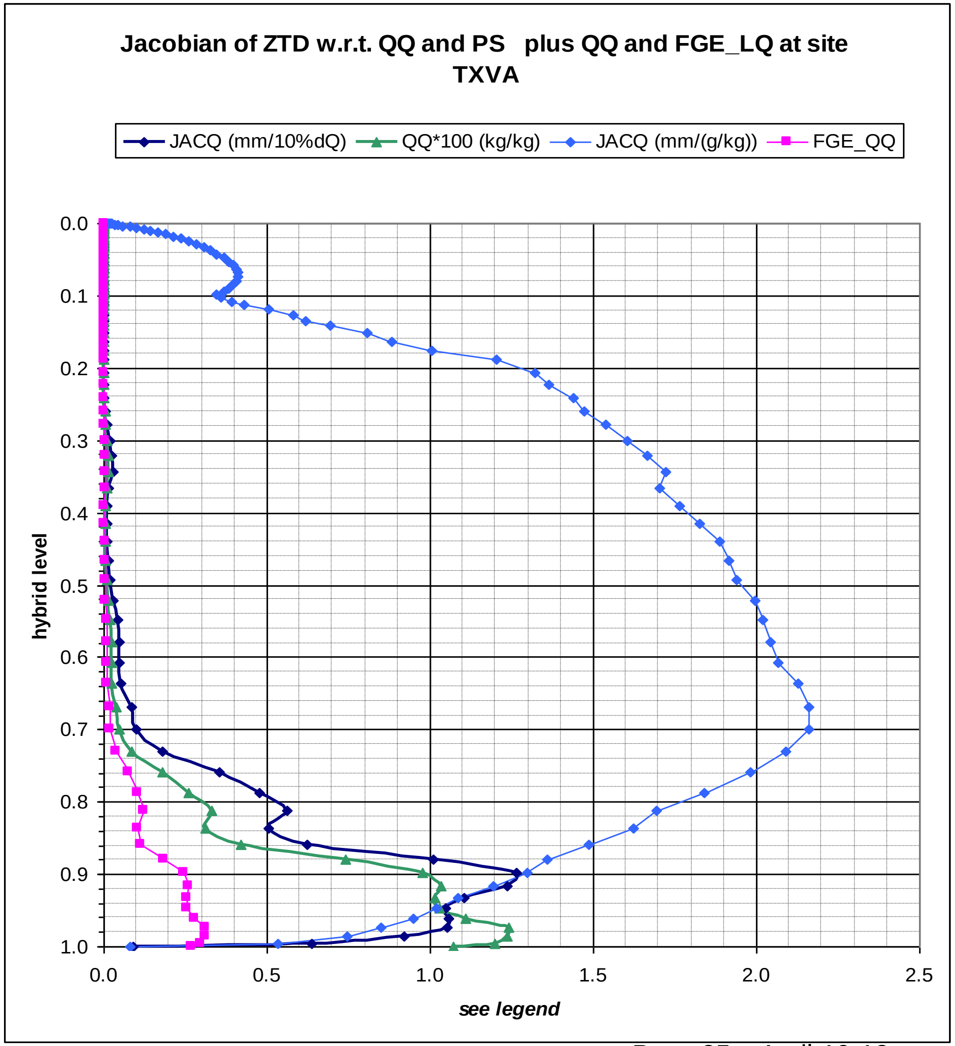
Assimilation Experiment Results

4D-Var, 3D data thinning for GB-GPS, summer 2011 (latest)

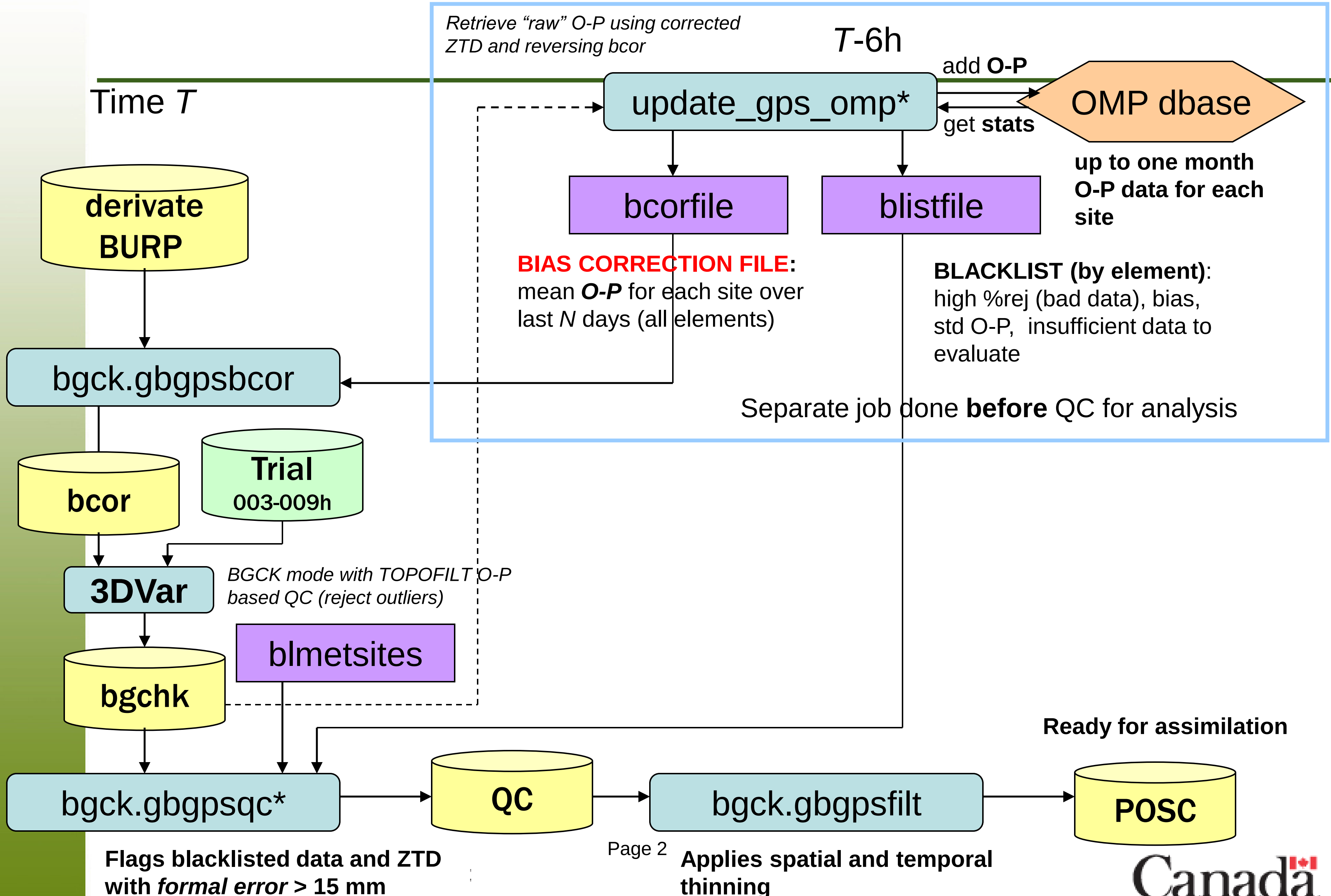


- Std(Obs-ANAL) < Std(Obs-FG) shows better fit of ANAL to observations compared to FG as result of assimilation
- Reduction in StdDev is 25-45% on average; some reduction (~5%) occurs even without GB-GPS assimilation due to more accurate Q, Ps fields in analysis, but most of the reduction comes from assimilation of the NOAA network GB-GPS data.
- **FG** = 6 hour REG-LAM forecast ZTD

ZTD Jacobian (w.r.t. humidity Q)

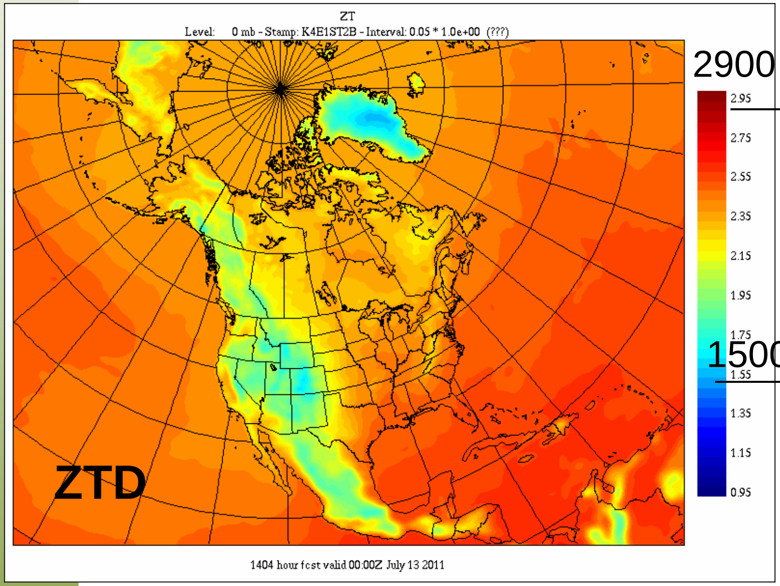


Quality Control for Assimilation: Operations



Model (6h forecast) ZTD Errors

ZTD = ZHD(Ps) + ZWD(PW)



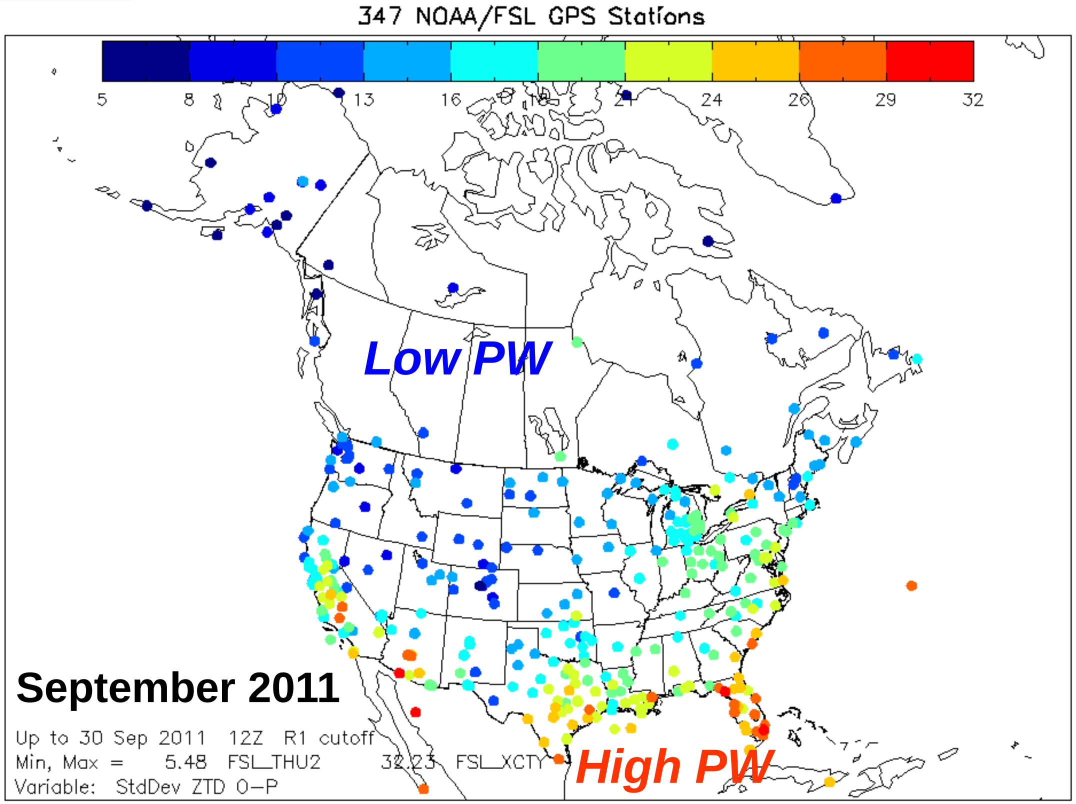
Mean NWP 6h forecast ZTD 15 May – 13 July 2011

- Model **Ps** error = 0.75 hPa
- Model **PW** error = Function (∫Q(z) error = Function LQ error & Q) = 3 mm (avg) in summer
- ZHD error = $2.4 \cdot 0.75 \approx$ 2 mm
- avg ZWD error = $6 \cdot 3 = 18$ mm
- avg ZTD model error = 18 + 2 = 20 mm
- avg ZTD observation error = 15 mm

ZHD (mm) $\approx 2.4 \cdot$ Ps (hPa)

ZWD (mm) $\approx 6 \cdot$ PW (mm)

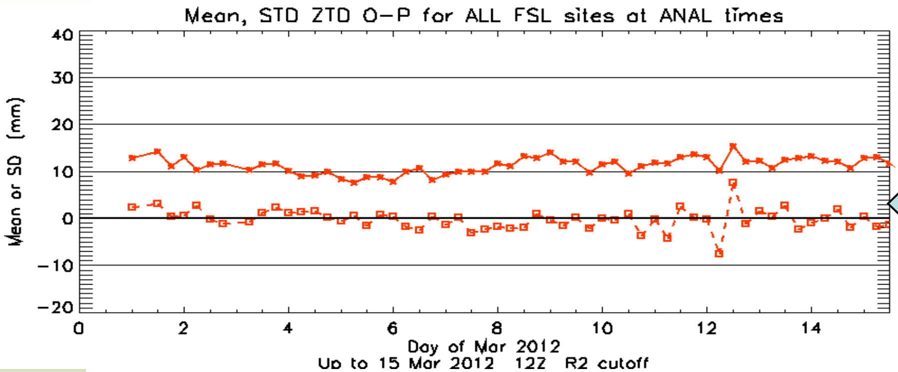
GPS ZTD Observation Error Model

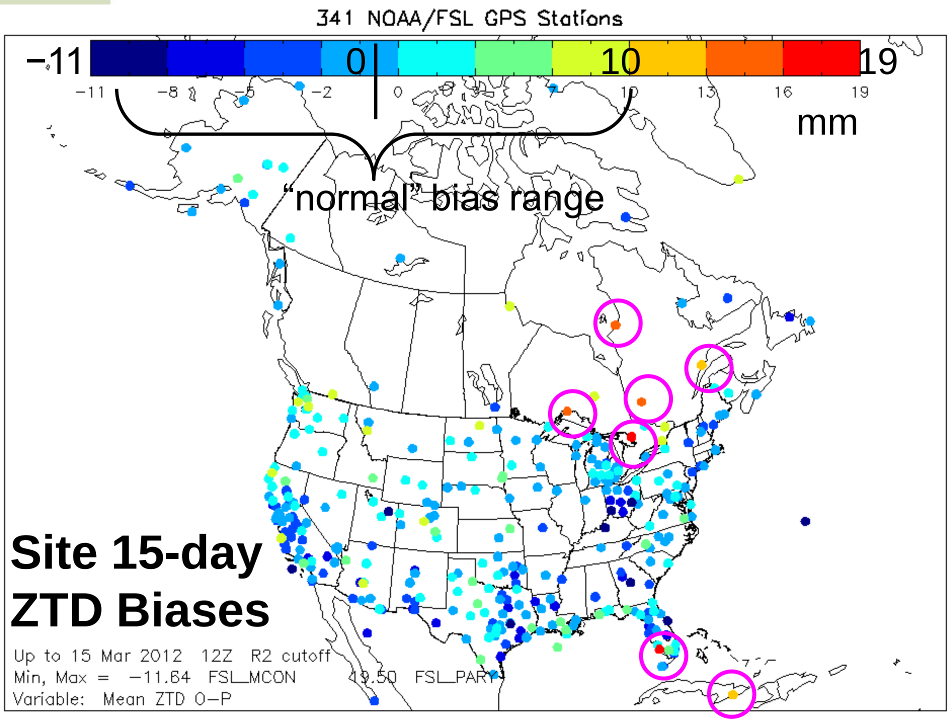


StdDev ZTD (obs-F6h)

- We assume monthly StdDev ZTD (obs-F6h) is a good measure of ZTD observation error for NWP purposes
- We observe that StdDev ZTD (obs-F6h) is generally higher at sites with higher mean PW
- We use this to create a ZTD error model that makes use of a linear regression of site StdDev ZTD (obs-F6h) with site mean ZWD(PW)
- Result is ZTD observation error that increases linearly with observed ZWD (where ZWD = ZTD – ZHD(Ps))

GPS ZTD Observation Biases





- **Bias = Mean (obs-F6h)**
F6h = 6h NWP (REG-LAM) forecast
- Overall network ZTD bias is near zero
- <u>but</u> there are biases at individual GPS sites
- Abs(Bias) > 10 mm suggests serious problem with the data for the site
- Biases must be removed with a bias correction system prior to data assimilation
- Sources of ZTD bias include
  - biases in 6h forecast Ps, Q fields
  - biases introduced by model ZTD operator
  - biases in ZTD estimates (issues with GPS receiver, location/siting and raw receiver data processing)
- Incorrect receiver antenna height (erroneous site info) produces model ZTD operator bias error (incorrect Δz)