9B.3

IMPACT OF GROUND-BASED GPS PRECIPITABLE WATER VAPOR AND COSMIC GPS REFRACTIVITY PROFILE ON HURRICANE DEAN FORECAST

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1. INTRODUCTION AND MOTIVATIONS

Accurate, dense, and continuous observation of water vapor is important to realize good initial condition in numerical weather forecast and to monitor and understand global hydrological cycle. Both ground-based and space-based GPS measurement of water vapor (or refractivity) is considered as one of the key observations because GPS observation technique is calibration free and it works under all weather conditions, not like as other passive remote sensing technique.

Figure 1 shows our OSSE (Observing System Simulation Experiments) for hurricane Katrina case. Anticipated island GPS stations in islands, that are shown as solid orange boxes in Figure 1(c), were helpful to improve moisture field in the analysis field, and the forecast from the improved analysis field showed significant improvement of the hurricane intensity forecast (Figure 2),

A new ground-based network of GPS stations has been installed in the Caribbean Sea (Caribbean network) since 2007 (Figure 3), and we can now use near real-time and continuous GPS precipitable water vapor (PWV) data as one of the observations for numerical weather forecast. Because the GPS stations are well distributed in islands, it is anticipated that GPS PWV from the network helps to improve hurricane forecasts.

On the other hand, a GPS occultation observation system, Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) was successfully launched in April 2006, and refractivity profile over the globe has been available with near real-time. The combination of these two GPS observations is expected to show more positive impact on tropical cyclone forecast.

In the study we explain GPS data and our hurricane forecast system in section 2. We then show results of PWV comparison between GPS and model analysis in section3. Section 4 introduces hurricane Dean case and the Dean forecasts are shown in section 5. We discuss on mechanism how GPS PWV intensify hurricane Dean in section 7, and conclude the study in section 8.

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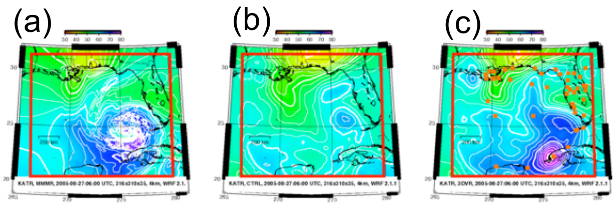

Figure 1: PWV distribution in (a) reference, (b) background, and (c) analysis after data assimilation of anticipated ground-based GPS stations in OSSE for hurricane Katrina in 2005.

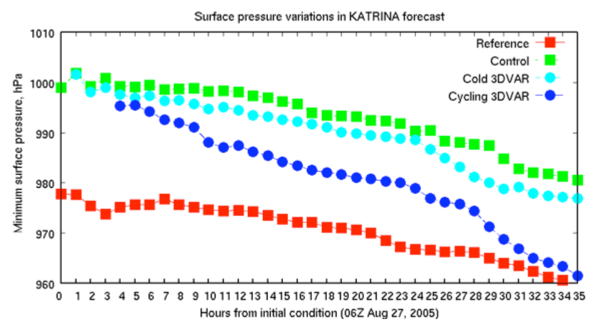

Figure 2: Intensity forecast in the OSSE for the Katrina case (Figure 1). Minimum pressure in the reference is shown with red curves, control forecast (without GPS PWV data assimilation) is shown as green curves, and cold and cycling 3DVAR forecasts show with light and dark blue curves, respectively.

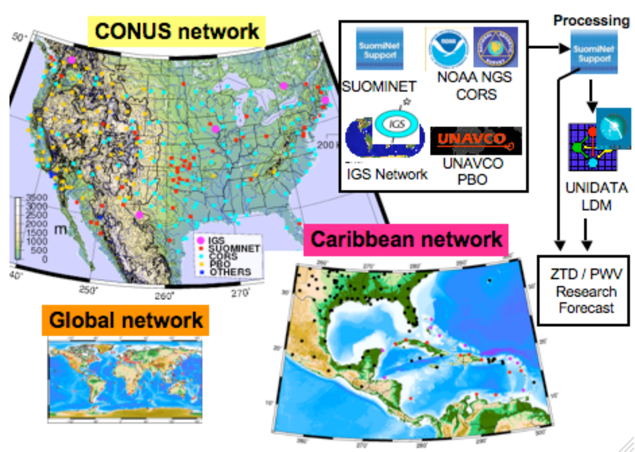

Figure 3: Ground-based GPS networks processed in UCAR/COSMIC. Zenith tropospheric delay (ZTD) and precipitable water vapor (PWV) for the network are distributed through homepage and LDM.

2. DATA AND FORECAST SYSTEM

2.1 *Ground-based GPS data*

Tropospheric estimate in Ground-based GPS data processing is zenith tropospheric delay (ZTD), which is integrated refractivity of the atmosphere into zenith, where refractivity is a function of temperature, water vapor pressure and pressure. ZTD can be mapped into precipitable water vapor (PWV) with pressure and temperature observations at the GPS station (Bevis *et al*., 1992). Figure 4 depicts schematic diagram of GPS observable. Advantages of GPS against other traditional water vapor sensors are that GPS PWV is continuously available in all weather conditions. Note that PWV retrieved from GPS is considered as averaged value in the inverse-cone with radius of about 25 km at 3 km height.

GPS data and surface meteorological observation data in SUOMINET and other multiple networks (Figure 3) are gathered is UCAR/COSMIC, processed with BERNESE GPS Software, and ZTD and PWV data with 30-minute bins are available with latency of about one hour via SUOMINET web site and UCAR UNIDATA Local Data Manager (LDM) system.

New GPS network has been deployed in Caribbean Sea area (Figure 3) since 2007. We thus focused on the Caribbean Sea, and first compared their GPS PWV with those from analysis field of numerical weather forecasts, and performed data assimilation and forecast experiment for hurricane cases.

2.2 *COSMIC refractivity profile*

We also tried data assimilation of refractivity profile from COSMIC to verify additional impact of the data for hurricane forecast against ground-based GPS PWV. Profiles of refractivity are derived from profiles of bending angle with some assumptions (details are available from Kursinski et al. 1997).

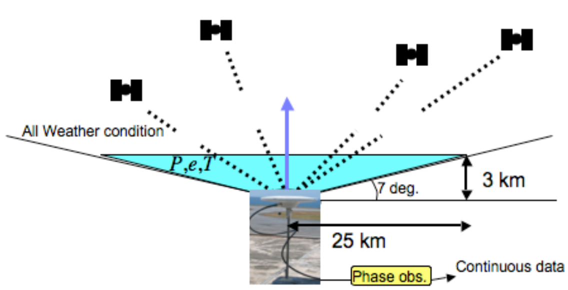

Figure 4: GPS tropospheric estimates (ZTD) and PWV) mapped from ZTD are considered as averaged values in inverse-cone with radius of about 25 km at 3 km height (by assuming scale height of water vapor) from antenna.

2.3 *Data assimilation and forecast system*

The Weather Research and Forecasting (WRF) model and its 3DVAR data assimilation system are used for the study. The domain size is 361x261 (12 km of horizontal grid) x 38 (vertical), centered in the north of Caribbean Sea.

Schematic diagram in Figure 5 shows the data assimilation and forecast system in the study. The analysis and forecast fields of NCEP Global Forecast System (GFS) are used as initial condition (IC) and lateral boundary conditions (LBC). We performed hourly cycling 3DVAR with 6-hour time window for continuous data assimilation.

The background error statistics were made with 10-day forecasts in August 2007 for the domain with NMC method. Figure 6 shows increment of specific humidity with data assimilation of GPS PWV at 12 UTC of September 4, 2007. The horizontal scale of moisture propagation seems to match with GPS observations (Figure 4).

Figure 7 shows sea level pressure and PWV distribution from NCAR/MMM real-time hurricane forecast for Dean. Negative correlation between `WV and sea level pressure near hurricane center is observed. It suggests that PWV distribution around the hurricane is relatively smooth for a few hundred km of radius from the hurricane center, and that moisture distribution in Figure 6 is reasonable.

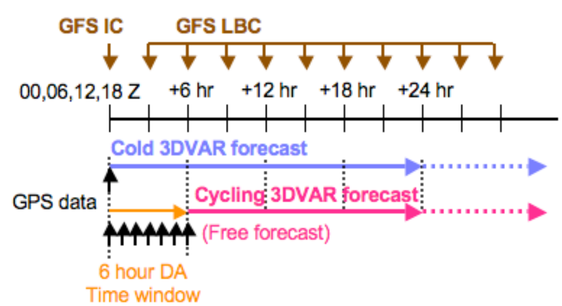

Figure 5: Hurricane forecast system using WRF 3DVAR data assimilation and forecast system. Background (initial condition, IC) and lateral boundary conditions (LBC) come from analysis and forecasts of NCEP GFS forecasts. Cold 3DVAR is one time data assimilation at initialization time (00, 06, 12, and 18 UTC), and cycling 3DVAR here means continuous data assimilation every one hour with 6-hour data assimilation time window.

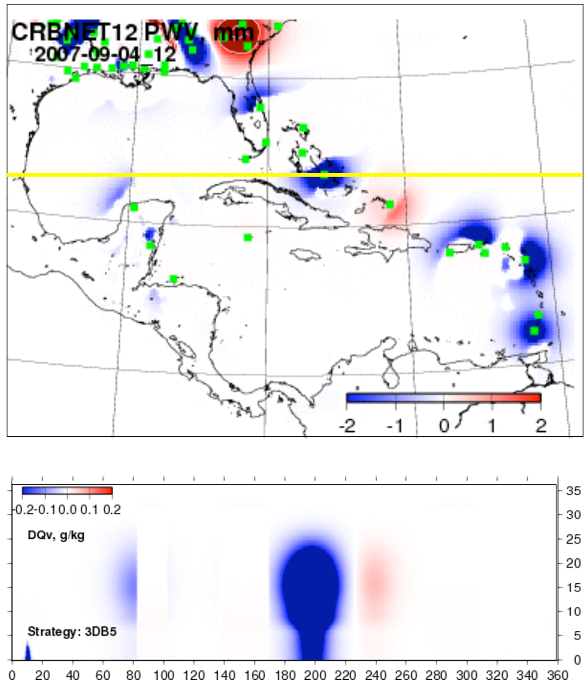

Figure 6: Increments of PWV (top) and moisture profile (specific humidity) in the east-west cross section (bottom, along yellow line in top panel) in cold 3DVAR at 12 UTC of September 4, 2007. Green boxes in the top panel show GPS stations. Horizontal and vertical axes in the bottom figure show model grid number (12 km for horizontal grid size).

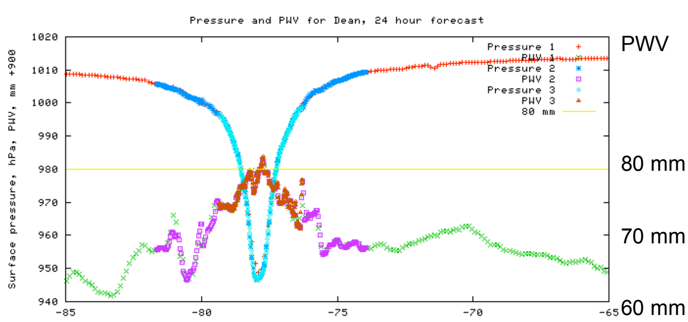

Figure 7: Sea level pressure and PWV along the east-west line centered in the hurricane Dean center from NCAR/MMM real-time hurricane forecasts. Different colors show different nesting domain. The highest horizontal resolutions is 4 km around the center of the hurricane.

3. COMPARISON OF GPS PWV WITH MODEL ANALYSIS

Figure 8 shows PWV comparison between GPS and NCEP ETA analysis field. Red histogram is for continental US (CONUS), and it does not show any significant biases and time dependency of the biases. On the other hand, it is clear that green histogram showing statistics for southeastern area (SE), including the Caribbean GPS network, indicates wet biases of the analysis field, and its dependency with time. The highest wet biases are at 00 UTC (-1.3 mm). RMS difference is also the largest at 00 UTC.

Table 1 summarizes PWV comparison between GPS and NCEP analysis field for the SE area. Similar biases are observed in both ETA and GFS analysis fields. The largest biases are seen at 00 UTC. Because such biases are not seen in CONUS area and quality of GPS estimates is considered as similar in any stations under careful maintenances and processing, the biases are considered to come from model analysis.

These results suggest that there are more rooms to improve moisture profiles in the Caribbean area where enough moisture observations are not available. Further comparisons are needed to explain the origin of the biases in the SE area.

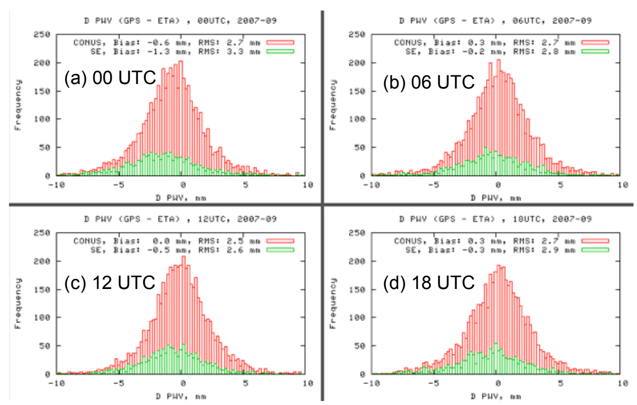

Figure 8: PWV comparison between GPS and NCEP ETA analysis field for (a) 00, (b) 06, (c) 12, and (d) 18 UTC. Histograms colored red and green are for continental US area and southeastern area (latitude < 32° N, longitude > -100°) in the network (Figure 3), respectively.

(a) ETA

	Mean	00 UTC	06 UTC	12 UTC	18 UTC
August	-0.63	-1.62	-0.49	-0.24	-0.21
September	-0.61	-1.33	-0.20	-0.53	-0.34

(b) GFS

	Mean	00 UTC	06 UTC	12 UTC	18 UTC
August	-0.68	-1.15	-0.45	-0.64	-0.54
September	-0.61	-0.69	0.06	-1.03	-0.70

Table 1: Mean PWV difference between GPS and NCEP (a) ETA and (b) GFS analysis field.

4. HURRICANE DEAN CASE

There are very few hurricanes observed in Caribbean GPS network in 2007; Dean, Noel, and Felix as shown in Figure 8. Caribbean GPS stations were still extending at the time, and only Dean case was good for intensified experiment.

Hurricane Dean was the strongest tropical cyclone of the 2007 Atlantic hurricane season. It strengthened into a major hurricane, reaching category 5 status on the Saffir-Simpson Hurricane scale before passing just south of Jamaica on August 20 (see map in Figure 10).

Figure 10 show time-series of PWV at GPS station in Jamaica (JAMA). PWV at Dean rapidly increased to 72.4 mm when Dean approached JAMA. GPS data was not available after that due to some damages of the GPS station. Because surface pressure data was not available for 1 hour before the data missing, we used the same surface pressure observed in the last observation. Hence, true PWV is considered to be higher than 72.4 mm at the last observation by considering the negative correlation between PWV and sea level pressure.

Figure 11 shows distribution of COSMIC refractivity profiles for one day of August 19, 2008. 11 profiles were available for the day, but only one profile (red square) is in the data assimilation time windows of 6 hours.

5. DEAN FORECAST

A significant impact of ground-based GPS PWV on hurricane Dean intensity forecast is observed at initialization of 18:00 UTC of August 19, 2007. The time window of GPS data assimilation includes relatively large PWV observation at Jamaica (Figure 10). Cloud images in Figure 12 suggest that significant amount of water vapor changes into cloud water with the GPS PWV data assimilation.

Figure 13 shows intensity forecast for the hurricane Dean, where forecasts with cold 3DVAR are not shown because meaningful differences were not observed due to lacks of observation in its data assimilation time window. The improvements of surface pressure at hurricane center are seen at the time when GPS PWV is assimilated (GPS PWV and GPS PWV+REF in Figure 13). It shows 10 hPa improvement when free forecast started, and about 22 hPa improvement in 24 hour forecast.

Figure 13 also shows that the best intensity forecast is observed when data assimilation of both GPS PWV and COSMIC refractivity is performed. It suggests that each GPS retrieval has its own benefit for hurricane Dean forecast.

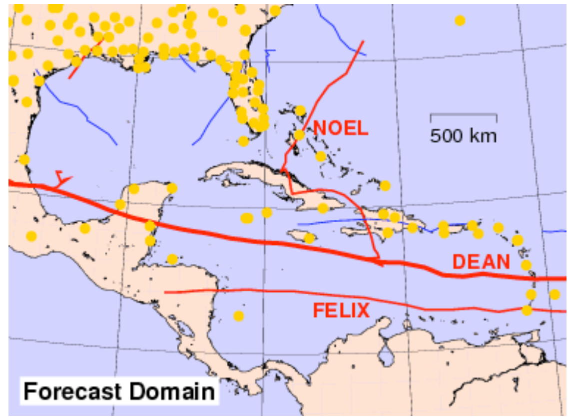

Figure 9: Hurricane (red) and tropical cyclone (blue) path in the Caribbean network domain in 2007. GPS stations are shown with solid yellow circles.

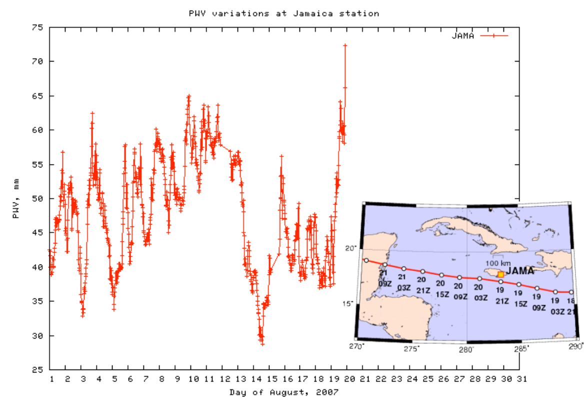

Figure 10: Time-series of GPS PWV at Jamaica (JAMA) station. PWV was about 73 mm at 21:15 of August 19, 2007 when Dean approached at JAMA. Data was missing after that.

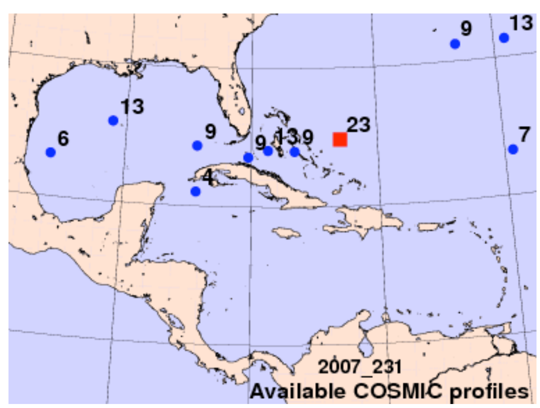

Figure 11: Distribution of available COSMIC refractivity profile (solid blue circles) in the forecast domain in the day of August 19, 2007. Numbers show hour of the observation time. Solid red square show data in data assimilation time window of 6 hours (from 18 to 24 UTC of the day).

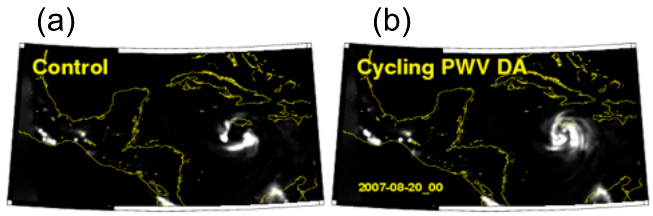

Figure 12: Cloud images valid at 00 UTC of August 20, 2007 (at the end of the data assimilation time window in cycling 3DVAR) for (a) control and (b) cycling 3DVAR with GPS PWV.

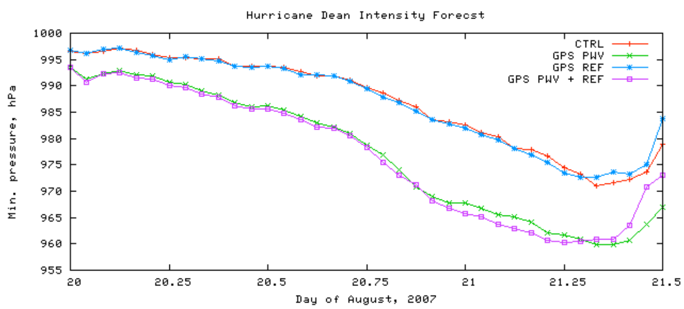

Figure 13: Intensity forecasts for the hurricane Dean in control forecast (red curve, CTRL), cycling 3DVAR forecasts with GPS PWV (green, GPS PWV), with COSMIC refractivity (blue, GPS REF), and with both GPS PWV and COSMIC refractivity (purple, GPS PWV + REF).

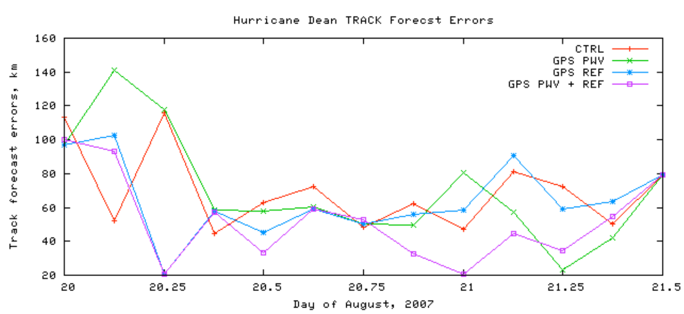

Figure 14: Same as Figure 13 but for track forecast error of hurricane Dean.

Forecast period	CTRL	GPS PWV	GPS REF	PWV+REF
20.0 - 20.5	81.5	69.5	103.3	67.7
20.5 - 21.0	61.3	52.8	54.6	44.4
21.0 - 21.5	62.6	67.9	50.9	38.6

Table 2: Mean track forecast errors (km) every 12 hours (unit for forecast period is day of August, 2007). Red and purple numbers show the best and the 2nd best track forecasts, respectively, in each period.

Figure 14 shows track forecast errors for hurricane Dean. Data assimilation of both GPS PWV and COSMIC refractivity shows the best track forecast in the experiment as shown in Table 2.

6. DISCUSSIONS

From the hurricane Dean forecast results, it is shown that both GPS PWV and COSMIC refractivity are helpful for the hurricane forecast. Because some researches have already reported positive impacts of COSMIC refractivity on tropical storm forecast, we focus on benefit of ground-based GPS PWV in islands and potential ocean platform stations on hurricane forecast.

6.1 *Temporal evolution of PWV increment*

Figure 15 shows temporal evolution of PWV increments (forecast with GPS PWV data assimilation minus control forecast). An almost concentric circle at Jamaica station (southwest in the maps) shows about 14 mm of PWV increment at the end of 6-hour data assimilation time window. Similar amount of increment is also found at Puerto Rico (northwest in the map). At the time center of the hurricane Dean was near Jamaica (Figure 10).

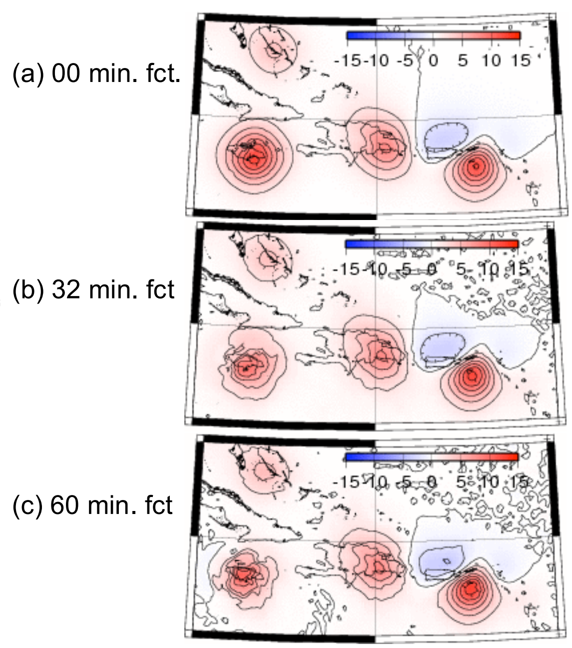

Figure 15: Temporal evolution of increment (3DVAR minus control) of PWV. Contour interval is 2 mm.

With time evolutions, the concentric circle at Jamaica changes to much more complex pattern than that at Puerto Rico (see (b) and (c) in Figure 15). Also amount of the increments decrease significantly in the concentric circle at Jamaica. The facts suggest that moisture provided in data assimilation of Jamaica PWV plays an important role to intensify hurricane Dean though phase change of water from water vapor to liquid.

On the other hand, the concentric circle at Puerto Rico sustain its pattern. The moisture added in the background gently changes depending on environmental flows in the area.

6.2 *One point data assimilation*

Because key station for hurricane Dean forecast is JAMA, we tried one point GPS PWV assimilation of JAMA station, and traced the phase change of water.

Figure 16 shows temporal evolutions of increments induced by one point and one time JAMA GPS PWV data assimilation at 21:00 UTC, August 19, 2007. Part of the increased moisture at the initialization change to cloud water and rain water, released latent heat (as shown as warm color in bottom temperature increment plots in Fig. 16), and intensified wind inside of the hurricane. Increase of temperature is about 2 K up to radius of 150 km from the hurricane center and up to 7 km of height.

The results suggest that one point PWV observation near the tropical storm center is invaluable for intensity forecasts of the tropical storms. Much more positive impacts are expected if such stations are available near the hurricane tracks.

6.3 *OSE and OSSE experiment for Dean*

We also tried one point data assimilation in OSE. The reference field comes from real-time WRF forecast (Figure 17) operated by NCAR/MMM with higher horizontal grid size of 4 km. The observation data with noises of 1.5 mm were generated for the same locations in the current GPS network. It was assimilated into the background. The forecast result was consistent with that from true data assimilation (not shown here).

One suggestions from OSSE was that number of the current observation are still not enough to improve forecast of hurricanes because we cannot change locations of real GPS stations after genesis of tropical cyclone.

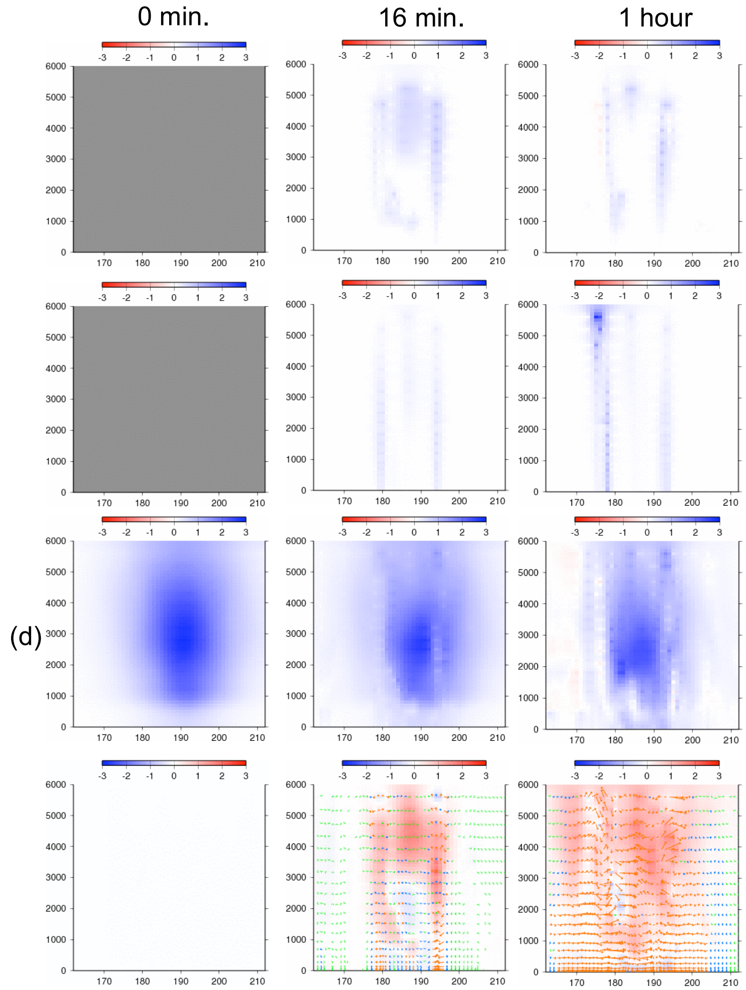

Figure 16: Temporal evolution of increment of (a) cloud water, (b) rain water, (c) water vapor, and (d) temperature plus wind at 0 minute (left), 16 minutes (center) and 1-hour integration time (right).

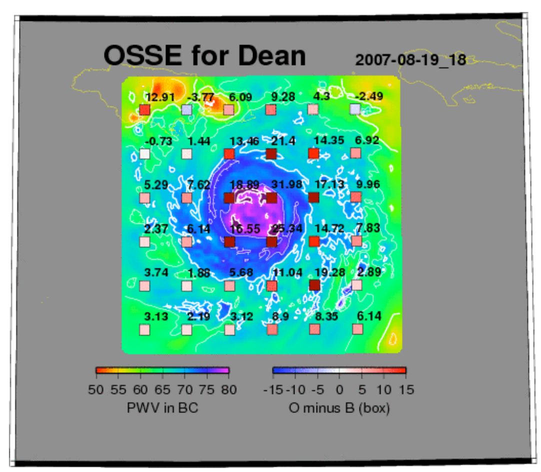

Figure 17: PWV from reference field used in OSE and OSSE studies for hurricane Dean case. Boxes shows observation (from reference field) minus background (from NCEP GFS analysis field) value (O minus B value) every 0.5 deg./0.5 deg. for latitude / longitude.

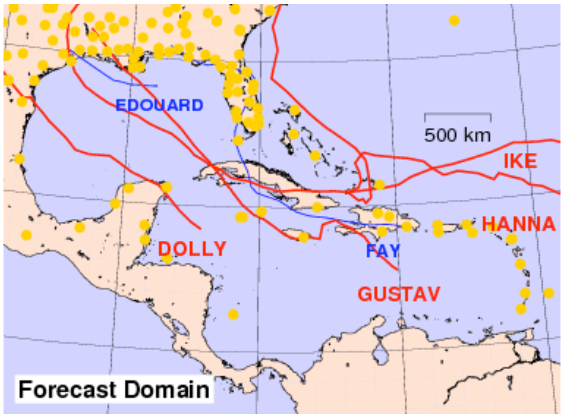

Figure 18: Same as Figure 9, but for hurricane season in 2008.

7. SUMMARY AND IMPLICATIONS

The Caribbean Sea and the Gulf of Mexico are areas we lack continuous and accurate moisture observation. It was shown that the new GPS network deployed around the Caribbean Sea and its near real-time processing system was helpful for the hurricane Dean forecast in 2007. Combined use of two types of GPS atmospheric retrievals; PWV from ground-based GPS and refractivity profile from COSMIC GPS radio occultation showed the best performance for the hurricane Dean forecast.

The key observation from ground-based GPS was GPS PWV available at the station that locates very close to the hurricane center. Because we do not have enough GPS stations in the Caribbean Sea and the Gulf of Mexico, positive impacts for hurricane forecasts are only available for the hurricanes that pass near the island GPS stations (it is also confirmed in case studies in 2008, Figure 18, not shown here). Future deployment of buoy-based and ocean platform GPS stations would be helpful to improve hurricane intensity forecasts. Because GPS can monitor PWV continuously and precisely, such ocean platform networks are also helpful for monitoring development of tropical storm including its genesis phase. More refractivity profiles in the ocean are also helpful to improve intensity and track forecasts of tropical storms and environment around tropical storms.

8. REFERENCES

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