INTERNATIONAL JOURNAL OF EARTH AND ATMOSPHERIC SCIENCE
Journal homepage: www.jakraya.com/journal/ijeas

ORIGINAL ARTICLE

Impact of GPS Radio Occultation Data Assimilation in the Prediction of Two Arabian Sea Tropical Cyclones

D. Srinivas[1], Venkata B. Dodla[1*], Hari Prasad Dasari[2] and G C Satyanarayana[1]

[1]K L University, Green Fields, Vaddeswaram-522 502, A.P., INDIA.
[2]Physical Sciences and Engineering Division, King Abdullah University of Science and Technology, Saudi Arabia.

*Corresponding Author:

Prof. Venkata B. Dodla

Email: dvbrao@kluniversity.in

Received: 30/04/2016

Revised: 13/06/2016

Accepted: 30/06/2016

Abstract

Numerical prediction of the movement and intensification of tropical cyclone over North Indian Ocean (NIO) is very important for the emergency management system in order to prevent the damage to properties and loss of lives. Numerical models are the tools to generate forecasts at near real time, which provide the guidance. Weather Research and Forecasting (WRF) model is the current state of art model used in the present study. GPS radio occultation (GPSRO) data are assimilated into the WRF model and data assimilation (WRFDA) system. The present study emphasizes the utilization of GPSRO observations in the prediction of tropical cyclones over NIO. Numerical prediction of the movement and intensification of two extremely severe cyclonic storms ‘Chapala’ and ‘Megh’ had genesis in the Arabian Sea are taken up as case studies. The results show that GPSRO observations have the positive impact in improving the initial conditions and so the forecast skill of tropical cyclones, in reducing the track errors and improving intensification .

Keywords: Data Assimilation, 3DVAR, Tropical Cyclone, GPSRO, Prediction**.**

1. Introduction

Tropical cyclones are the most destructive of all natural disasters as they cause loss of human lives and livestock and inflict extensive damage to property. Prediction of the movement and strength of tropical cyclones with a good lead time facilitates the administrators to take necessary precautionary and mitigation measures. Recent advancements in computer technology, availability of a large quantity of observations from both conventional and remote sensing platforms and atmospheric modeling (model physics, dynamics and data assimilation methods) all together have significantly contributed to improving the short range weather forecasts, especially the skill of tropical cyclone prediction. Prediction of the movement and intensification of tropical cyclones over North Indian Ocean (NIO) is very important due to the increased habitation and location of industries in the coastal regions as tropical cyclones cause most of the damage near the landfall point.

The Global Position System (GPS) Radio Occultation (RO) is relatively a new technique through which the atmospheric temperature and humidity profiles are retrieved. The technique involves a low earth orbit (LEO) satellite receiving a signal from a GPS satellite and that the signal which passes through the atmosphere gets refracted along its way before reaching the LEO. About 24 GPS satellites are distributed in six circular orbital planes with ~55º inclination with respect to the equator. The GPS satellites are placed at an altitude of 20,200 km orbiting in a near circular path with ~12 hour sidereal period. Each GPS satellite continuously transmits signals at two L-band frequencies, L1 at 1.57542 GHz (~19cm) and L2 at 1.227 GHz (~24.4cm). An occultation occurs when a GPS satellite rises or sets across the limb with respect to a LEO satellite. The physical process is that a ray that passes through the atmosphere is subject to refraction due to atmospheric density variations. During an occultation (~3 min) the ray path slices through the atmosphere and measures the change of the delay (phase) of the signal path between GPS and LEO which includes the effect of atmosphere. Using the raw measurements of phase of the two signals from L1 and L2, the bending angles are retrieved (applying the clocks correction, orbit determination and geometric delay). From these bending angles, the ionospheric corrections are applied (removing the electron density variations) and the neutral bending angle is retrieved. By assuming the local spherical symmetry, Abel transforms will provide an estimate of the atmospheric refractive index profile. From the refractive index the vertical profiles of the atmospheric temperature and humidity are retrieved (Kursinski *et al*., 1997; 2000). Currently the data assimilation techniques directly take the refractive index and/or bending angle as input parameter.

Numerical prediction of tropical cyclones has been the focus of study due to its societal implications. Some of the studies have clearly brought out the usefulness of MM5 and WRF models and the impact of data assimilation for improvement of initial conditions (Bhaskar Rao and Hari Prasad, 2005, 2007; Bhaskar Rao and Vijay, 2012; Sushil *et al*., 2014; Dasari and Dodla, 2014; Pradhan *et al*., 2015). Bhaskar Rao and Hari Prasad (2005, 2007) have demonstrated the impact of data assimilation and the role of convection and boundary layer processes in the predictability of tropical cyclones over North Indian Ocean. Bhaskar Rao and Vijay (2012) have compared different versions of the WRF model and showed the superiority of HWRF in tropical cyclone prediction. Dasari and Dodla (2014) brought out the use of potential vorticity diagnostics in the prediction of tropical cyclones over Bay of Bengal using MM5 model. Sushil *et al*. (2014) has shown the improvement in simulating the location and rainfall amount over west coast of India with assimilation using 3DVAR system along with the WRF model. Pradhan *et al*. (2015) showed that the assimilation of ARMEX (Arabian Sea Monsoon Experiment) special observations produced a better simulation of the characteristics of a well-organized Mid-Tropospheric Cyclone over the Arabian Sea off Gujarat coast than without data assimilation.

National Center for Environmental Predictions (NCEP) Global Data Assimilation System (GDAS) operationally assimilates the RO data globally and total daily atmospheric soundings of ~2,000. The RO instruments from which the observations are archived are the COSMIC (since May, 2007), Metop/GRAS (since February, 2010), GRACE-A (since February, 2010), SAC-C (since May, 2011), C/NOFS (since May 2011) and TerraSAR-X (since May, 2011). Most of the models assimilate the bending angles or refractivity from GPSRO satellites. Since the availability of GPSRO data, a few studies have shown the impact of GPSRO data on weather prediction. Ha *et al*. (2014) studied the impact of GPSRO observations using the WRF model and 3DVAR system and shown that assimilation of GPSRO observations improved the heavy rainfall forecast in terms of both the location and rainfall amounts. Zhou and Chen (2014) showed the impact of assimilation of GPSRO refractivity in the WRF model and the 3DVAR system for two case studies and reported that the trade wind inversion is better predicted in summer case, and in winter case, the propagation of a cold front is better simulated as the moist tongue associated with the cold front is better delineated and the vertical profiles of temperature and moisture are largely improved with GPSRO assimilation. Rennie (2008) reported appreciable positive impact of the assimilation of the FORMOSAT-3/COSMIC refractivity measurements in the UK Met Office Unified Model assimilation system which has led to the data being assimilated operationally at the UK Met Office. GPSRO data from Megha-Tropiques ROSA satellite had been assimilated into the NCMRWF GFS (T574) model and results from the Observation System Simulation Experiments (OSSE) for fifteen days showed significant improvement in forecast skill beyond 72 hours (Johny and Prasad, 2014). These studies show the usefulness of GPSRO data for short range weather prediction applications. For the present study, the impact of GPSRO data assimilation is assessed in the prediction of the movement and intensification of two extremely severe cyclonic storms Chapala and Megh which had a genesis over the Arabian Sea in the post monsoon season of 2015. The details of the model, data and a brief methodology used for the present study is described in section 2, details of tropical cyclones are described in section 3, the results are provided in section 4 and the conclusions are given in section 5.

2. Model, Data and Methodology

In this section, the details of numerical weather prediction model, datasets and brief description of methodology used in the present study are presented.

2.1 Details of Model

The Advanced Research Weather Research and Forecasting (or ARW) modelling system, developed and sourced from NCAR, is used in the present study. The ARW modelling system has versatility to choose the domain region of interest, horizontal resolution, and interactive nested domains with various options to choose parameterization schemes for cumulus convection, planetary boundary layer, explicit moisture, radiation, and surface processes. ARW is designed to be a flexible, state-of-the-art atmospheric prediction system that is portable and efficient on available parallel computing platforms, and a detailed description was provided by Skamarock *et al*. (2008). The model consists of fully compressible non-hydrostatic equations, and the prognostic variables include the three-dimensional wind, perturbation quantities of pressure, potential temperature, geopotential, surface pressure, turbulent kinetic energy, and scalars (water vapor mixing ratio, cloud water, etc.). The model equations are formulated using massbased terrain following coordinate system and solved in Arakawa-C grid using Runge-Kutta third-order time integration techniques. The model has several options for spatial discretization, diffusion, nesting, and lateral boundary conditions. The ARW modeling system supports horizontal one way and two-way nesting capabilities that allow the resolution to be focused over a region of interest by introducing an additional grid (or grids) into the simulation.

WRF Data assimilation system (WRFDA) has been used for assimilating the observations. WRFDA is the advanced version of the WRF's 3DVAR module, which has the capability to assimilate several types of observations that include conventional surface, upper air, aircraft, wind profiler, atmospheric motion vectors, radio occultation refractivity; and the radiances from all sensors (Barker *et al*., 2012). For the purpose of retrieving the track position, central sea level pressure and maximum wind, the Geophysical Fluid Dynamics Laboratory (GFDL) vortex tracker program (Bao *et al*., 2013) is used.

2.2 Data

The initial and time varying boundary conditions for model integrations are taken from GFS Forecasts at 0.25 degree horizontal resolution and at every six hour interval as available from http://rda.ucar.edu/data/ds084.1 (NCEP, 2015). Similarly the GPSRO BUFR Observations retrieve from the NCEP GDAS system sourced from http://nomads.ncdc.noaa.gov/data/gdas at every 6 hour interval. Currently the NCEP GDAS provides the GPSRO bending angles from ten different satellites like TerraSAR-X, TenDEM-X, GRACE-A, GRACE-B, METOP-A, MEOP-B, COSMIC-1 to COMIC-6. The occultations available in the model domain for 4 cycles of 20151028 (notation represents yyyymmdd) for Chapala, and 20151105 for Megh cyclone case studies are shown in Fig 1. The background error covariance file (CV3) "be.dat" with the NCEP background error covariances computed based on the NMC method (Parrish and Derber, 1992) is used in the present study.

2.3 Methodology

2.3.1 Model Experiments

The ARW model is adapted and designed to have two-way interactive two nested domains with horizontal resolutions of 15 and 5 km, the inner domain covering the Arabian Sea region (Fig 2) and with 48 vertical levels. The details of model configuration and physical parameterization schemes are provided in Table 1. Model integrations are performed in a continuous 132-hour period for Chapala and 120-hours for Megh, with a pre-forecast data assimilation period of 24 hours. For each case study, two types of numerical experiments are conducted, one with the GPSRO assimilation called as GPS and other without GPS observations referred to as CNT. For Chapala case study, the assimilation period started at 0000 UTC on 28th October, 2015 with five update cycles (i.e.) up to 0000 UTC on 29th October, 2015. The forecasts are then generated for 132 hours starting from 0000 UTC on 29th October. Similarly for Megh cyclone, the assimilation period started at 0000 UTC on 5th November, 2015 and updated at every six hour interval up to 0000 UTC on 6th November, 2015 and the model forecasts are generated for 120 hours. The forecasts are performed in order to study the impact of GPSRO data in the evolution of two tropical cyclones, Chapala and Megh that occurred over Arabian Sea in 2015. The control runs are started at the same time as the assimilation start time. The GFDL vortex tracker program has been used to retrieve the model forecasted cyclone center (latitude, longitude) and intensity (surface wind speed and central surface pressure). The model derived parameters are validated by comparison with IMD estimated track positions, maximum wind speed and minimum surface pressure.

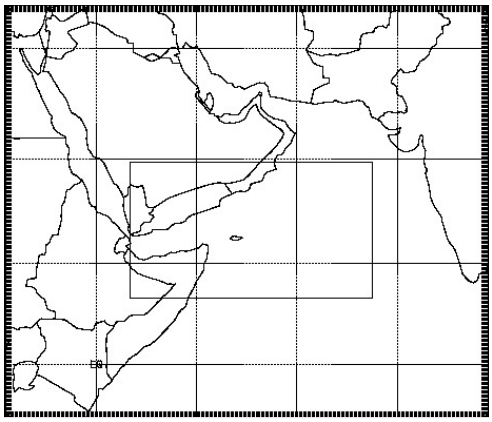

Fig 2: Model domains.

3. Description of Tropical Cyclones

This section briefly describes the details of genesis, development and movement of cyclone Chapala and Megh.

3.1 Description of Tropical Cyclone Chapala

Chapala, was the strongest cyclone that had landfall in Yemen after the severe cyclonic storm of May 1960 (IMD, 2015a). The extremely severe cyclonic storm (ESCS) 'Chapala' had its genesis as a low pressure area over the southeast Arabian Sea (AS) on 26th October. Chapala developed into a depression on 28th October, 2015 itself, moved north-northwestwards and further intensified into severe -

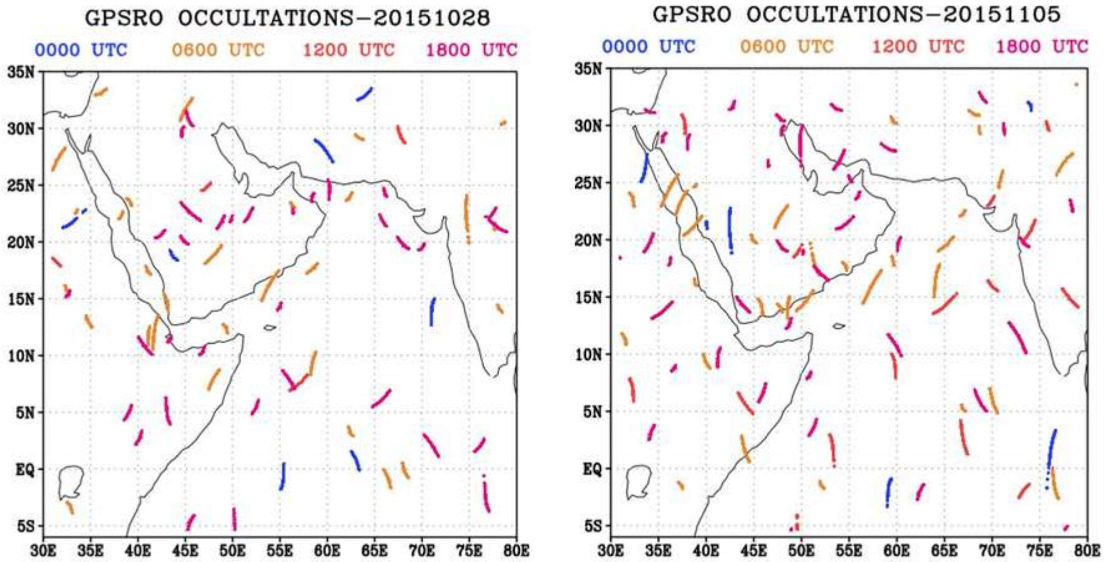

Fig 1: GPSRO occultations observed in the model domain 1 region valid for 20151028 (left panel) and 20151105 (right panel).

Table 1: The details of model

Model	WRF (ARW), WRFDA	
Version	3.6.1	
Dynamics	Primitive equation, non-hydrostatic	
Vertical resolution	48 levels	
Domains	Domain1	Domain2
Horizontal resolution	15 km	5 km
Radiation	Dudhia scheme for shortwave RRTM scheme for long wave	
Initial and boundary conditions	NCEP GFS Global Forecast	
Cumulus convection	Kain-Fritsch (new Eta) scheme	
Planetary boundary layer	Mellor-Yamada-Janjic TKE scheme	
Explicit moisture	Lin scheme	
Surface layer physics	Monin-Obukhov (Janjic) scheme	
Land Surface	Noah LSM	

cyclonic storm by evening and further intensified into very severe cyclonic storm on 29 October 2015 and became an extremely severe cyclonic storm on 30th October 2015 and continued moving westwards on the same stage up to 0300 UTC of 1 November 2015. The maximum attained wind speed of 115 kt and minimum central surface pressure of 940 hPa are estimated at the mature stage of Chapala. The storm continued to weaken gradually, moving westnorthwestwards, Chapala crossed the Yemen coast between 0100 and 0200 UTC on 3 November 2015 as a very severe cyclonic storm with maximum wind speed of 65 kt (120 kmph) and minimum surface pressure of 984 hPa (IMD, 2015a).

3.2 Description of Tropical Cyclone Megh

According to the reports of India Meteorological Department (IMD, 2015b), a depression formed over the east central Arabian Sea at 0000 UTC on 5th November and moved westwards/westsouthwestwards and intensified into a cyclonic storm (CS). Named as "Megh" at 1200 UTC on 5th November, it further intensified into a severe cyclonic storm (SCS) at 0600 UTC of 7th, identified as very severe cyclonic storm (VSCS) at 1500 UTC of 7th and rapidly intensified into an extremely severe cyclonic storm (ESCS) at 0300 UTC on 8th November. The maximum attained wind speed was 95 kt and minimum surface pressure was 964 hPa as estimated at the mature stage. Megh continued to weaken to deep depression and crossed the Yemen coast around 0900 UTC of 10th November, 2015.

4. Results

In this section, the results are described starting with initial differences for both Chapala and Megh and the subsequent model forecasts.

4.1 Cyclone Chapala

The WRF model is integrated for 132 hours starting from 2015102900 (yyyymmddhh) with 24 hour assimilation of GPSRO from 0000 UTC on 28 to 0000 UTC on 29 October. Two types of experiments are conducted, one with GPSRO assimilation (GPS) and another without assimilation (CNT).

4.1.1 Differences in the Initial Conditions

The height-longitude section of maximum wind speed (MW, m/s) for CNT and the difference between CNT and GPS is shown in Fig 3. In the CNT, the maximum wind speed of more than 20 m/s (indicative of cyclone force wind speed) extended vertically up to 300 hPa level (Fig 3, left panel) which shows the depth of the storm. The difference plot (Fig 3, right panel) shows that the wind speed is higher by 2-6 m/s all around the cyclone and extend up to 600 hPa (200 hPa) level in eastern (western) side of the cyclone, which clearly refers to stronger cyclone simulation with GPS. The relative humidity (RH) of the CNT shows the RH to be more than 95% in the lower levels extending vertically up to 800 hPa level, but on the eastern side the RH extends up to 600 hPa. The RH is more than 70% on the eastern side of the cyclone extending vertically up to 400 hPa level (Fig 4, left panel). The difference in RH shows that RH is more in GPS experiment and extend to higher levels than CNT, although between 60E-65E, the eastern side of the CNT had more humidity and extending vertically up to 200 hPa level. (Fig 4, Right panel). The GPSRO modified the humidity fields where the CNT is having less (west side). Similarly the height-longitude section of vorticity (VOR, /s) shows the vorticity is positive and extended up to 200 hPa level (Fig 5, left panel). The Differences in vorticity shows that GPS is having more vorticity and extend up to 600 hPa level and CNT is having more beyond up to 450 hPa level (Fig 5, right panel). This indicates stronger initial vortex with GPSRO data assimilation. The differences in MW, RH and VOR shows that assimilation of GPSRO data increased the strength of the cyclone core and the region around especially at lower levels.

4.1.2 Numerical Prediction of Movement and Intensification

The model predicted track of the Chapala cyclone along with IMD estimates is shown in Fig 6(a) and the corresponding distance position errors (track errors) are shown in Fig 6(b). Initially, the GPS and CNT positions are located at the same place and away from IMD position. With model integration, the GPS and CNT show the movement of track from north to northwest and northnorthwest direction. The GPS (CNT) shows the track deviated from IMD after 78 (54) hours. Correspondingly the vector track errors (TE, km) shows the TEs are showing less than 100 km up to 48 hours and increasing thereafter, the increase in TE for GPS is because of slower movement of model cyclone (Fig 6b).

The model predicted time series of maximum wind (MW, m/s) is slightly overestimated at the initial time (Fig 7a) in both the GPS and CNT experiments. The GPS and CNT underestimated the MW up to 48 hours and slightly overestimated after 72 hours. Similarly the model predicted central surface pressure (CSP, hPa) shows the pre-deepening stage and deepening stages, whereas both CNT and GPS produced stronger cyclonic storm (Fig 7b) than observed. The GPS experiment shows slightly stronger cyclonic system than CNT.

4.2 Cyclone Megh

The WRF model is integrated for 120 hours starting from 2015110600 (yyyymmddhh) with prior 24-hourly assimilation of GPSRO period. Two types of experiments are conducted, i.e. with GPSRO assimilation (GPS) and without assimilation (CNT).

4.2.1 Differences in the Initial Conditions

The height-longitude of MW (m/s) for CNT and the difference between CNT and GPS valid at 0000 UTC of 6th November, 2015 are shown in Fig 8. In the CNT, the MW is slightly less in the GPS around 65ºE than CNT (Fig 8, left panel). The difference plot (Fig 8, right panel) shows that the wind speed is higher in the CNT by 4-8m/s on both sides of the cyclone center and extending up to 700mb. The MW is less by 2-8m/s in the upper levels from 400mb-200mb level in CNT. The RH of the CNT shows RH more than 90% extending vertically up to 300 hPa level (Fig 9, left panel). The difference in RH shows that CNT is having less humidity in the middle levels from 850-500 hPa level by about 25% (Fig 9, Right panel). The assimilation of GPSRO modified the humidity fields of the initial conditions, especially in the middle levels. This is considered important as mid-level humidity is important for the development of convection in cyclones. Similarly the height-longitude section of VOR(/s) shows that the vorticity is positive and extended up to 700 hPa level (Fig 10, left panel) and -

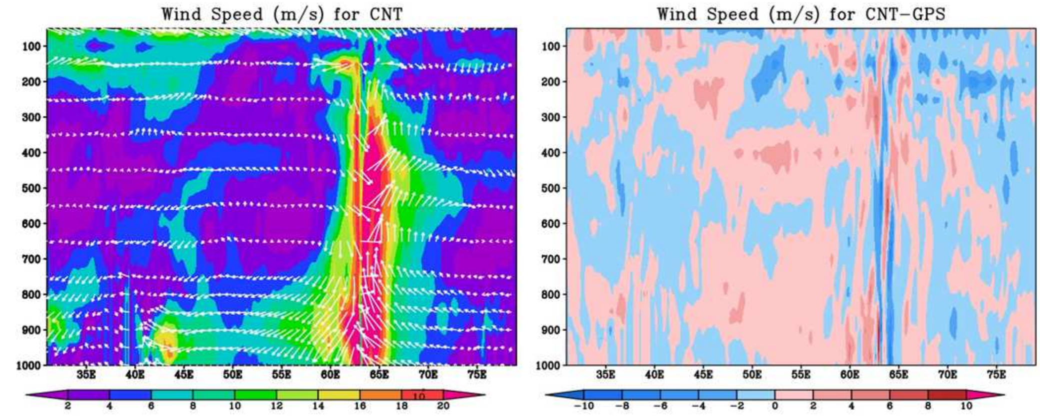

Fig 3: Height-Longitude cross section of maximum wind speed (m/s) for CNT (left panel) and the differences between CNT and GPS (right panel) valid at 20151029. The latitude center is fixed at the cyclone center of CNT.

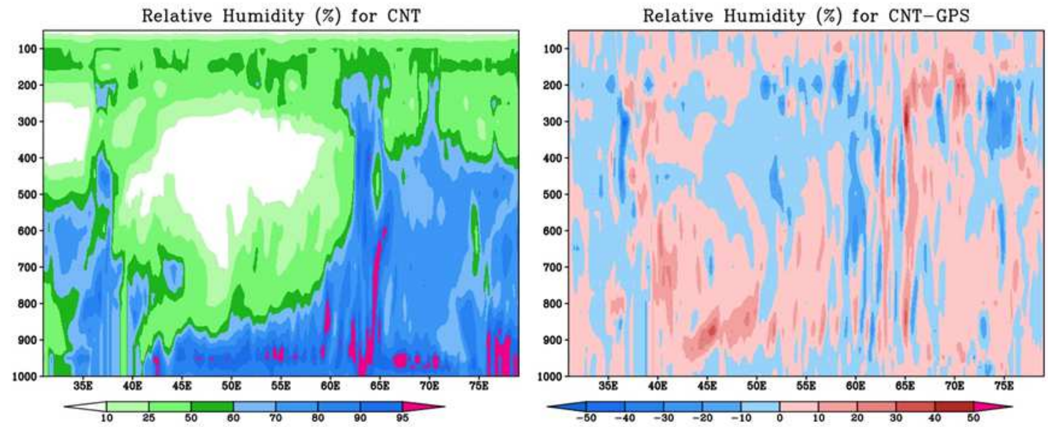

Fig 4: Same as Fig 3 but for Relative Humidity (%).

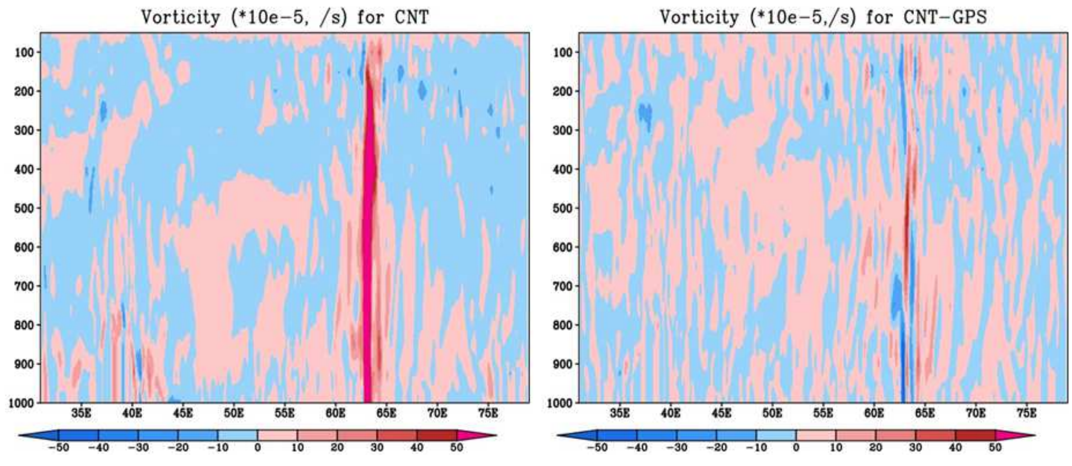

Fig 5: Same as Fig 4 but for Vorticity ($*10^{-5}$, /s).

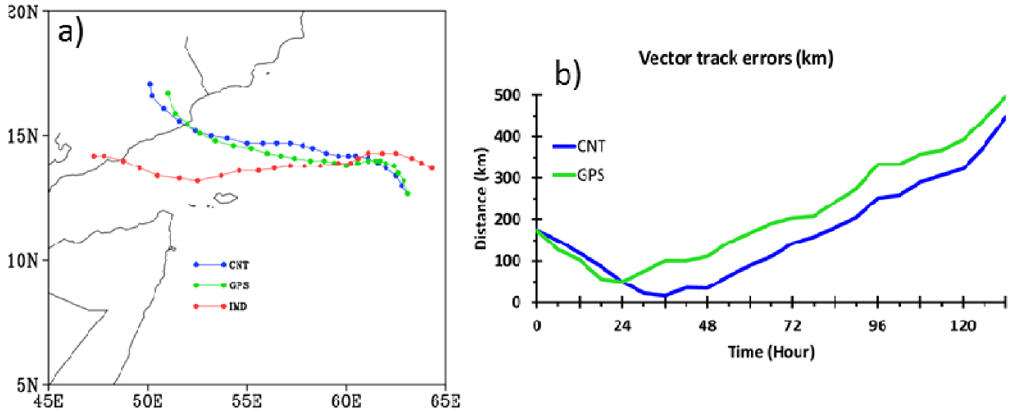

Fig 6(a): The model predicted track positions along with IMD estimates for Chapala, and (b) vector track errors (km).

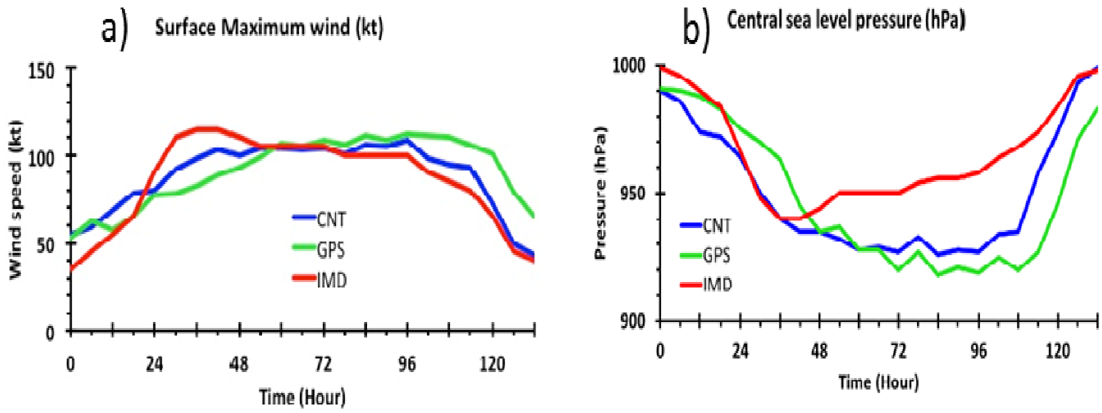

Fig 7: Model predicted (a) maximum wind (m/s) and (b) central sea level pressure (hPa).

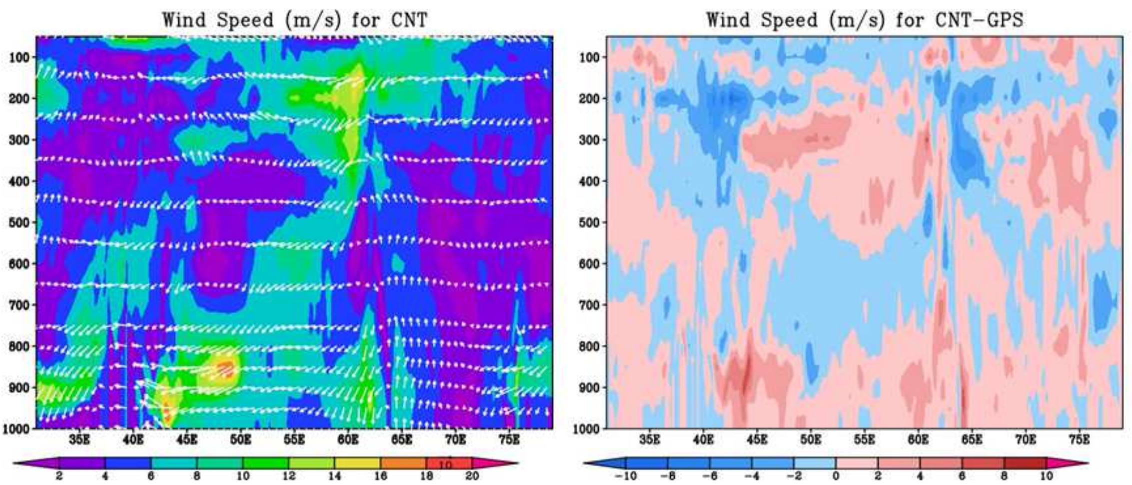

Fig 8: Height-Longitude cross section of maximum wind speed (m/s) for CNT (left panel) and the differences between CNT and GPS (right panel) valid at 20151106. The latitude center is fixed at cyclone center of CNT.

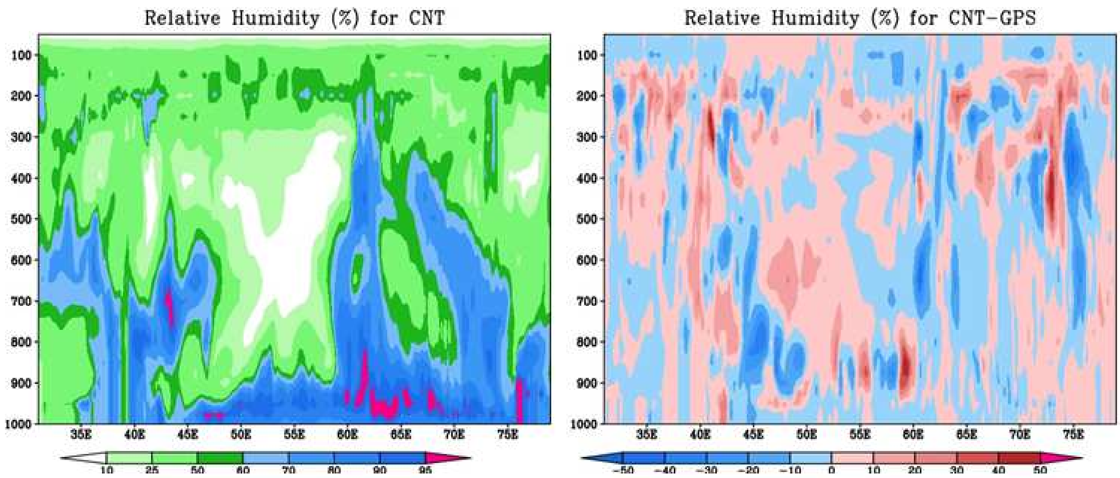

Fig 9: Same as Fig 8 but for Relative Humidity (%).

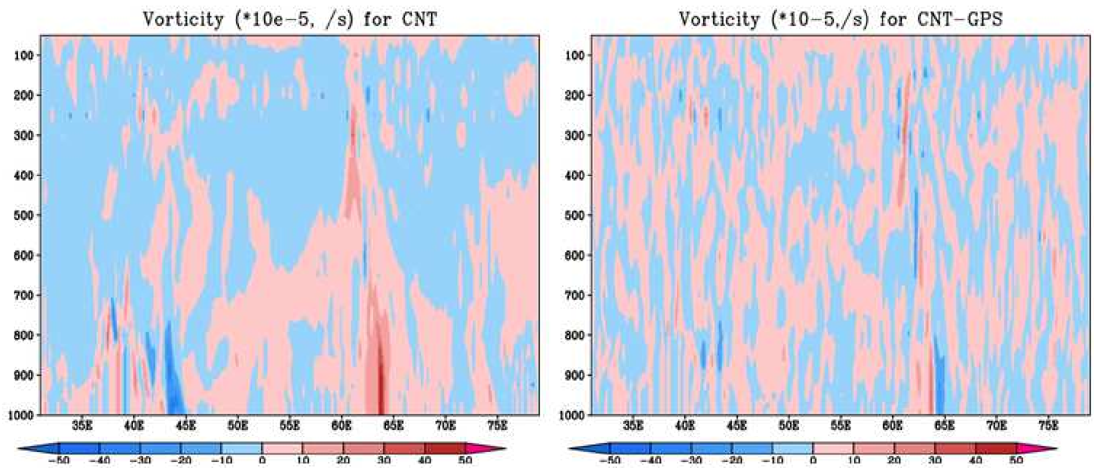

Fig 10: Same as Fig 9 but for Vorticity (*10^{-5}, /s).

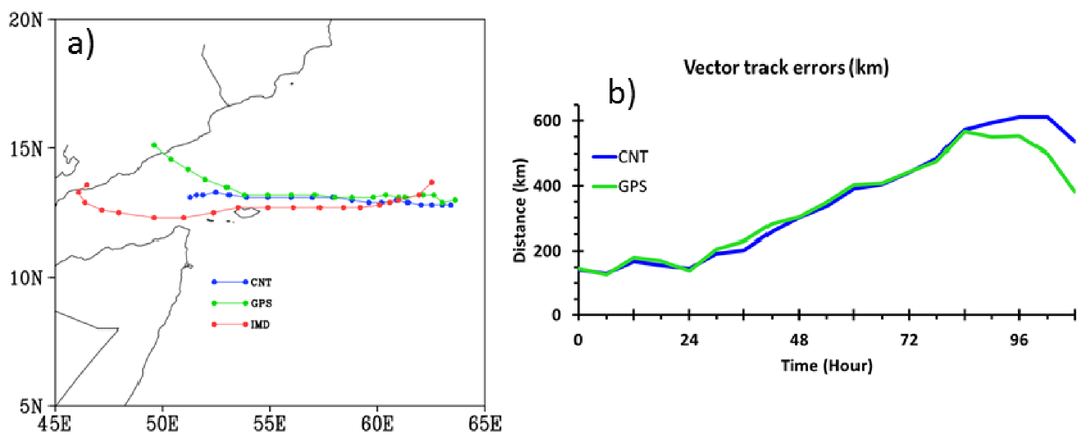

Fig 11(a): The model predicted track positions along with IMD estimates for Megh, and (b) vector track errors (km).

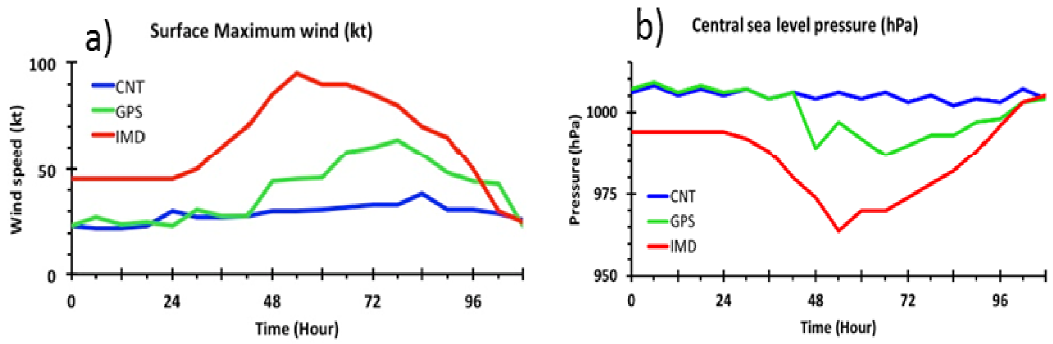

Fig 12: Model predicted (a) maximum wind (m/s) and (b) central sea level pressure (hPa).

again from 500-300 hPa level. The Differences in vorticity shows slightly less value, but with more horizontally extended vorticity and with slight eastward shift in GPS (Fig 10, right panel). The differences in MW, RH and VOR shows that assimilation of GPSRO data changed the cyclone core region. In this case, GPS experiment shows that the assimilation has contributed to the slightly weaker vortex at the initial time in contrast to "Chapala". These differences in the initial conditions with the assimilation of GPSRO contributed to changes in the subsequent forecasts.

4.2.2 Numerical Prediction of Movement and Intensification

The model predicted Megh cyclone track along with IMD estimates is shown in Fig 11(a) and the corresponding distance position errors (track errors) are shown in Fig 11(b). Initially, the GPS and CNT positions have differed from IMD position. With model integration, the GPS and CNT show the movement of track from west-northwest to westwards and again northwest direction for GPS and in CNT track had westward movement from the beginning. The tracks from GPS and CNT shows a similar movement up to 84 hours and the CNT slowed afterwards not crossing the coast, whereas the GPS had northwest track and crossed the coast around 0600 UTC on 10th November, 2015. This is significant as GPS had simulated the landfall in contrast to the absence of landfall in the CNT. Corresponding vector track errors (km) show that the initial position error is around 150 km and the errors are similar up to 78 hours. For CNT the errors increased thereafter, whereas GPS shows gradual decreases of errors afterwards (Fig 11b).

The model predicted time variations of MW and CSP are presented in Fig 12 for GPS and CNT along with IMD estimates. The MW and CSP are conspicuously different beyond 42-hours, although similar up to 42-hours in the GPS and CNT experiments. CNT experiment does not show any development of the cyclone system as indicated by the variations of CSP and MW. In contrast, GPS predicted intensification of the system from 42-hours agreeing with observations. The GPS experiment slightly underestimated the strength of the cyclone, but the time variations of intensification and decay are closer to observations. The MW of GPS shows intensification of the cyclone Megh with the increase of the MW and decrease of CSP. The results show that the assimilation of GPSRO improved the initial conditions in the structure of vortex, with slightly larger vortex and improvement of humidity in the middle levels, which have significantly improved the prediction of the evolution, both in terms of intensification and movement.

5. Conclusions

The impact of assimilation of GPS radio occultation (GPSRO) refractivity in the prediction of North Indian Ocean (NIO) tropical cyclone (TC) is assessed in terms of movement and intensification. Weather Research Forecasting (WRF) model is the current state of the art model with two way interactive two nested domains with horizontal resolution of 15 and 5 km is adapted in the present study. GPSRO data assimilated through the WRF model and data assimilation (WRFDA) system. Numerical prediction of the movement and intensification of two extremely severe cyclonic storms 'Chapala' and 'Megh' which had genesis in the Arabian Sea in 2015, are taken up as case studies.

The assimilation of GPSRO data has significantly modified the initial conditions of both the cyclones under study. The assimilation led to a stronger vortex in the case of "Chapala" and weaker vortex with improved humidity structure in "Megh" cyclone. The differences in the initial conditions, thus attributable to GPSRO assimilation, have contributed to improved forecasts of both the cyclone systems. In the case of "Chapala" cyclone, a stronger cyclone had been simulated with GPS which is closer to observations. Similarly, GPS had predicted a landfall of "Megh" cyclone which CNT could not predict at all. The GPS experiment could also predict the intensification after 42-hours from initial integration agreeing with observations, whereas the CNT experiment could not predict the development of the vortex. These two experiments with GPSRO data assimilation clearly brings out the impact of the data assimilation procedure and those from GPSRO in the prediction of the evolution of tropical cyclones over North Indian Ocean. The choice of the two cyclones over the Arabian Sea had been because very few cyclones occur over Arabian Sea than over Bay of Bengal and are less explored.

Acknowledgment

The authors acknowledge the data sources, GPSRO observations and GFS forecasts from National Centers for Environmental Prediction, observed track position and intensity estimates from India Meteorological Department.

References

Bao S, Stark D and Bernardet L (2013). Users guide for the community release of the GFDL Vortex Tracker. *The Developmental Testbed Center, National Centers for Environmental Prediction*, p24.

Bhaskar Rao DV and Hari Prasad D (2005). Impact of special observations on the numerical simulation of a heavy rainfall event during ARMEX-Phase 1. *MAUSAM*, 56: 121-130.

Bhaskar Rao DV and Hari Prasad D (2007). Sensitivity of tropical cyclone intensification to boundary layer and convective processes. *Natural Hazards*, 41: 429-445.

Bhaskar Rao DV and Vijay T (2012). Tropical cyclone prediction over bay of Bengal: A comparison of the performance of NCEP operational HWRF, NCAR ARW and MM5 models. *Natural Hazards*, 63: 1393-1411.

Dasari HP and Dodla VB (2014). A diagnostic study of bay of Bengal tropical cyclone (Orissa Super Cyclone) movement and intensity. *International Journal of Earth and Atmospheric Science*, 1: 115-131.

Ha JH, Lim GH and Choi SJ (2014). Assimilation of GPS radio occultation refractivity data with WRF 3DVAR and Its impact on the prediction of a heavy rainfall event. *Journal of Applied Meteorology and Climatology*, 53: 1381-1398.

India Meteorological Department (2015a). Extremely severe cyclonic storm, CHAPALA over the Arabian Sea (28 October - 4 November, 2015): A Report, *Cyclone Warning Division, India Meteorological Department, New Delhi*, p 53.

India Meteorological Department (2015b). Extremely severe cyclonic storm, MEGH over the Arabian Sea (05-10 November, 2015) A Report, *Cyclone Warning Division, India Meteorological Department, New Delhi*, p 53.

Johny CJ and Prasad VS (2014). Impact of assimilation of Megha-Tropiques ROSA radio occultation refractivity by observing system simulation experiment. *Current Science*, 106: 1297-1305.

Kursinski ER, Hajj GA, Schofield J, Linfield R and Hardy K (1997). Observing earth's atmosphere with radio occultation measurements using the global positioning system. *Journal of Geophysical Research*, 102: 23429-23465.

Kursinski ER, Hajj GA, Leroy SS and Herman B (2000). The GPS radio occultation technique. *Terrestrial, Atmospheric and Oceanic Sciences*, 11: 53-114.

National Centers for Environmental Prediction /National Weather Service/NOAA/U.S. Department of Commerce (2015). updated daily. *NCEP GFS 0.25 Degree Global Forecast Grids Historical Archives. Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory*. http://dx.doi.org/10.5065/D65D8PWK. Accessed 21 Mar 2016.

Pradhan PK, Dasamsetti S, Ramakrishna SSVS, Dodla VB and Jagabandhu Panda (2015). Mesoscale simulation of Off-Shore Trough and Mid-Tropospheric Cyclone associated with heavy rainfall along the West Coast of India using ARMEX reanalysis. *International Journal of Earth and Atmospheric Science*, 2: 1-15.

Rennie MP (2008). The assimilation of GPSRO at the met office. *Proceedings of GRAS SAF Workshop on Applications of GPSRO Measurements*, 16-18.

Skamarock WC, Klemp JB, Dudhia J, Gill DO, Barker DM, Duda MG, Huang X-Y, Wang W and Powers JG (2008). A description of the *Advanced Research WRF version* 3. NCAR Tech. Note NCAR/TN-475+STR, 113 pp., doi:10.5065/D68S4MVH.

Sushil K, Routray A, Rashmi C, and Jagabandhu P (2014). Impact of parameterization schemes and 3DVAR data assimilation for simulation of heavy rainfall events along West Coast of India with WRF modeling system. *International Journal of Earth and Atmospheric Science*, 1: 18-34.

Zhou C and Chen YL (2014). Assimilation of GPS RO refractivity data and its *Impact on Simulations of Trade Wind Inversion and a Winter Cold Front in Hawaii*. *Natural Science*, 6: 605-614.