Assimilation and simulation of Cyclone Gonu (2007) using the UAE WRFVAR system

Ahmad Awad AL-KATHERI*[1], AJJAJI Radi [2] and Abdullah DHANHANI[2]

[1] *Air Force and Air Defense Meteorological Department, UAE*

[2] *United Nations Development Programme, Abu-Dhabi, UAE*

ABSTRACT

On early June 2007, a severe cyclone "Gonu", formed over the south western Indian coasts, succeeded in reaching the north eastern coasts of the Arabian Peninsula. Using the recently developed Weather Research and Forecasting system, implemented in both assimilation and prediction modes at the United Arab Emirates Air Force and Air Defense, and operational over the Arabian Peninsula and a large part of the Indian Ocean, numerical experiments consisting in different warm cycling assimilations followed by short to medium range free forecasts are conducted for the initialization and simulation of this cyclone. The assimilation is using in addition to the available common GTS observational data, Global Positioning System Radio Occultation (GPS RO) Refractivity soundings provided by COSMIC/DAAC, and Quick Scaterrometer (QuickSCAT) near-surface wind observations, with their experimental high spatial resolution of 25 km, provided by the "Koninklijk Nederlands Meteorologisch Instituut" (KNMI) . The prediction part of WRF model takes benefit of the high resolution two-way nesting technique and the use of adequate physical parameterization dealing reasonably with such super active phenomena (Kain-Fritsch cumulus, Lin et al. microphysics schemes, Yonsei University planetary boundary layer). The results of the experiments suggest that the subsequent WRF model forecasts of Gonu cyclone track and accompanying precipitation are significantly impacted upon the initial analyses fields. QuickSCAT and GPS RO, when assimilated using tuned background and observation error statistics, especially have a very significant impact on the quality of these forecasts in term of the storm position and intensity.

Key words: 3D-Var, data assimilation, observation impact, numerical simulation, cyclone.

1. Introduction

Over the past two years, the United Arab Emirates invested considerable resources in implementing local Numerical Weather Prediction (NWP) systems. The new generation WRF system (Skamarock et al., 2005) is implemented and used operationally in both assimilation, with 3D-Var technique, and prediction. Huge efforts continue to be deployed for the installation and tuning of the assimilation part. The difficulties of this latter, part are inherent especially to the observational data acquisition and pre-processing, and to the heavy tasks of calibration and tuning of background and observation error statistics. Despite a slight disadvantage of U.A.E. WRF 3D-Var warm cycling especially for surface fields due, in our opinion, to the lack of surface analysis, the overall impact is beneficial when compared to the cold start mode from the Global Forecasting System (GFS) Global Statistical Initialization (GSI) analyses.

The conducted experiments are using version 2.2 of the WRF model and WRF 3D-Var released in late 2006. The configuration of the WRF 3D-Var system is based on an incremental formulation producing a multivariate incremental analysis in the WRF model space. The minimization of the cost function is performed in the space of preconditioned control variables (Stream-function, potential velocity, unbalanced pressure and specific humidity). Statistics of differences between 24 h and 12 h forecasts are used to estimate background error covariances via the so-called NMC method (Parrish and Derber, 1992).

Recently, tropical cyclone forecast models at high resolution have greatly improved due to major advances in high performance computing resources, but also to the various non conventional observational data experimented and used nowadays such as Tropical Cyclone Bogus data and all remote sensed satellites and Radar data categories. Yet, the success of simulating accurately the cyclone track and intensity may also depend on the error statistics

[1] *E-mail: dafra@afmet.ae
Current Author Affiliation: Lieutenant Colonel at U.A.E Air Force and Air Defense, Abu-Dhabi, United Arab Emirates.

of the different sources of information and on the accuracy of the storm location in the first guess which is involving the ability of the forecasting model to simulate accurately the movement of the cyclone.

The main purpose of this study is to demonstrate the ability of UAE WRF 3D-Var in analyzing Gonu cyclone (June 2007) and its surrounding atmosphere, and to assess the impact on the subsequent WRF model forecasts of the cyclone. UAE WRF 3D-Var analyses for Gonu cyclone initialization are tuned by acting on Background Error Statistics (BES) and on Observation Error Statistics (OES). Impacts of certain techniques like multiple outer loops and First Guess at Appropriate Time are also quantified. But especially, the sensitivity of the cyclone track to some relevant types of observations like GPS RO and near-sea Scatterometer winds is demonstrated.

This paper is organized as follows: The next section briefly describes the UAE WRF and WRF 3D-Var modeling systems. Section 2 gives a synoptic overview of cyclone Gonu followed, in section 3, by a detailed definition of the experimental context with the description of the technical aspects and relevance of each cycling experiment. Section 4 is dedicated to the results presentation and interpretation. And finally, the summary and conclusions are given in section 5.

2. U.A.E. WRF Numerical Weather Prediction operational suite.

2.1. Brief description of the WRF and WRF 3D-Var used in the experiments.

All the conducted experiments (described in details below) are based on the WRF version 2.2 released on 22 December 2006. This version became operational at the U.A.E. Meteorological Department on late January 2007. UAE WRF model is running operationally, since August 2006 over three two-way multi-nested domains with increasing horizontal resolutions of 40 km (domain d01), 13.3 km (d02) and 4.4 km (d03), centered on United Arab Emirates (24.5° N, 54.5° N) (Fig. 1). 38 hybrid sigma-pressure levels are considered on the vertical up to 50 hPa. The lateral boundary conditions for d01 are taken from the global NCEP GFS (0.5 × 0.5 degree) forecasts, at six hours frequency, up to 5 days. Ferrier microphysics scheme is chosen for all model domains, whereas Kain-Fritsch cumulus parameterization scheme is employed only for d01 and d02. For planetary boundary layer and surface physics, Yonsei University PBL and Noah LSM surface schemes are respectively used. Rapid Radiative Transfer Model (RRTM) long wave, and MM5 (Dudhia, 1993) shortwave radiation scheme are used. The model is run twice a day and produces forecasts up to 5 days with hourly post-processing

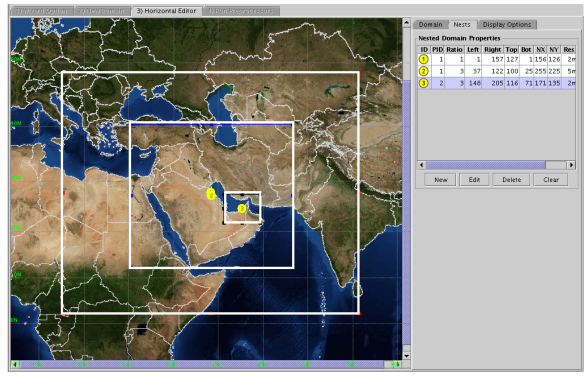

***Figure 1** UAE/WRF two-way nested operational model domains.*

UAE WRF 3D-Var is still in the stage of intensive validations. It became pre-operational since April 2007 and tunings of its different components are ongoing. It takes advantage of FGAT technique, multiple outer loops, use of unconventional satellite and Radar data, local background error statistics computed via the NMC method, adaptive tuning factors for the various observational data determined using Desroziers and Ivanov 2001, and Hollingsworth and Lonnberg, 1986, techniques. But, this version of WRF 3D-Var suffers from the incapacity to assimilate raw radiances, the lack of an initialization procedure to filter the 3D-Var analyzed noisy fields (Wee and Kuo, 2004), and the absence of a surface analysis.

2.2. Observational data

The set of observational data used to simulate Gonu cyclone comprises all the available GTS data (SYNOP, METAR, SHIP, BUOY, TEMP, PILOT, AIREP, AMDAR, SATEM, GEO AMV) complemented by GPS Radio Occultation soundings provided by the COSMIC Data Analysis and Archive Centre (http://cosmic-io.cosmic.ucar.edu/cdaac), and near-sea Scatterometer winds (QuickSCAT) processed in quasi real time by the KNMI Ocean and Sea Ice Satellite Application Facility (OSI SAF) .

The raw observation error statistics originate from NCEP but have been modified at NCAR after comparisons against long term statistics on innovations (Hollingsworth and Lonnberg 1986). The high resolution Geostationary Atmospheric Motion Vectors are provided by the METEOSAT 9 of Eumetsat. The pre-processing of GEO AMVs is inspired from the global data pre-processing implemented at ECMWF (Table 1).

__Table 1__ Rejection quality index threshold for the used Geostationary Atmospheric Motion Vectors

Infra Red winds	All available winds with Quality Index (QI) larger than 85
Visible winds	All winds below 700 hPa and QI larger than 70
Water Vapor cloudy winds	All winds above 400 hPa and QI larger than 85

Both CHAMP and SAC-C satellites Radio Occultation data types are included, but only Refractivity parameter is used. Table 2 is giving the number of GPS soundings assimilated at each analysis step during Gonu activity from 31 May 2007 at 0600 UTC to 07 June 2007 at 1200 UTC, and figure 2 is showing their assembled locations for 04 June 2007. Despite their few number (~ 20 per analysis time in the largest WRF domain), their impact is known to be very beneficial on the quality of the assimilation and simulation of tropical cyclones. The specification of error statistics applied for these data are following Kuo et al. 2005. It depends on both altitude and latitude.

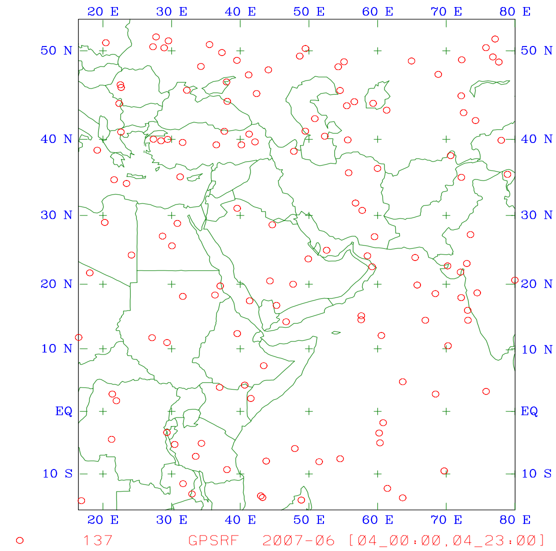

__Figure 2__ Locations of the GPS RO Refractivity data used in the 3D-Var assimilation for 04 June 2007.

__Table 2__ A list of the occultation refractivity observations from the CHAMP and SAC-C satellites used in the assimilation for cyclone Gonu on 04 June 2007.

Satellite	Observation time	Occultation location	Gonu track
CHAMP	20070603-2247 UTC	21.246°N, 51.920°E	18.5°N, 65.5°E at 0000 UTC
SAC_C	20070604-0828 UTC	19.798°N, 65.766°E	19.2°N, 64.9°E at 0600 UTC
SAC_C	20070604-0823 UTC	14.400°N, 66.944°E	
SAC_C	20070604-0844 UTC	23.904°N, 65.463°E	
CHAMP	20070604-1132 UTC	15.094°N, 57.622°E	19.9°N, 64.1°E at 1200 UTC
CHAMP	20070604-1140 UTC	13.247°N, 59.723°E	
SAC_C	20070604-1714 UTC	24.967°N, 52.575°E	20.5°N, 63.2°E at 1800 UTC
SAC_C	20070604-1726 UTC	22.540°N, 59.197°E	
SAC_C	20070604-1743 UTC	22.658°N, 70.190°E	
SAC_C	20070604-1835 UTC	24.147°N, 58.516°E	
SAC_C	20070604-1854 UTC	14.466°N, 57.597°E	
SAC_C	20070604-1856 UTC	18.502°N, 68.410°E	

The Scaterrometer sea winds provided by KNMI are different from those distributed from NASA and NOAA products since special emphasis is put on:

- Increasing the reliability of the wind vectors by quality control and rejection of rain-contaminated Wind Vector Cells.
- Improving accuracy by noise reduction through spatial averaging and meteorological filtering
- Reducing wind direction selection errors by meteorologically-balanced wind direction Ambiguity Removal.

The QuickSCAT data used in this study have a spatial resolution of 25 km and their recommended and assigned error is 2.5 m/s in speed and 5 degrees in direction.

The observational data are sorted into 7 subsets, around each analysis time (4 per day), corresponding to 7 one-hour time slots, using the WRF 3D-Var observation preprocessor (3DVAR OBSPROC). This is a pre-requisite of the application of First Guess at Appropriate Time (FGAT) technique (Fig 4).

2.3. Background Errors Statistics (BES)

In AFAD WRFVAR system, two options of background error statistics (BES) for control variable are available. For control variables in physic space, the NCEP BES (option CV3) could be interpolated, and for control variables in eigenvector space, the local AFAD BES (option CV5) were derived based on three months lagged forecast datasets. Multiple previous cyclone simulations using WRF 3D-Var recommended the use of locally generated BES for the best track assimilation and prediction (Guo et al., 2005, Guo et al., 2006). In this study we will not study the impact of different BES on Gonu track and intensity; we will consider that CV5 are better and suitable for simulating the cyclone. However some tuning suggested by Desroziers and Ivanov (2001) technique will be applied for background error variances and length scales.

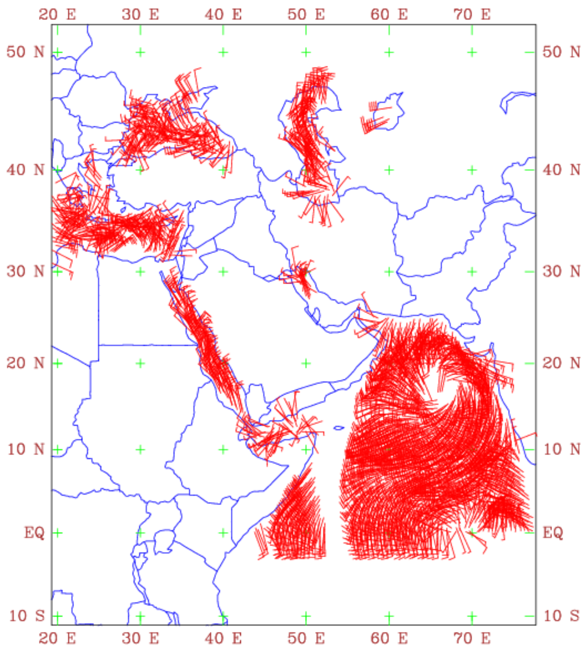

Figure 3 Locations of the QuickSCAT data used in the 3D-Var assimilation for 04 June 2007. (Data were thinned by 3DVAR OBSPROC).

2.4. First Guess at Appropriate Time

While the standard WRFVAR only uses a short-range forecast valid at the analysis time to compute the innovations (observation minus background), WRFVAR-FGAT (Lee et al., 2004) has a number of forecasts available and selects, for each observation, a forecast whose time is the closest to the observation time. Theoretically, FGAT is better because the innovations are computed in a consistent way and the frequently reported observations are taken into account in the analysis (METAR, AIREP, AMDAR, Satellite data). The advantage is known to be interesting when data from fast moving observation platforms and satellites are assimilated. A priori, we suppose that FGAT will be beneficial for our study since thousands of high resolution QuickSCAT data (very important for cyclone track assimilation) will be ingested.

As it could be noticed in figure 4, the FGAT design of the conducted experiments is performing consecutive couples of analysis-forecast. Each forecast is 9 hours range to cover the following analysis window (which is 6 hours centered on the analysis time) with background forecasts.

2.5. Experimental design

A total of six experiments were conducted to assess the impact of the different WRF 3D-Var ingredients. They consisted in analyzing, six hourly, the cyclonic situation over Indian Ocean and Arabian Peninsula from 31 May 2007 at 0600 UTC to 07 June 2007 at 1200 UTC with a warm cycling technique. A cold start (First guess interpolated from GFS GSI analyses) experiment is conducted and considered as reference. Table 3 is summarizing the characteristics of each experiment.

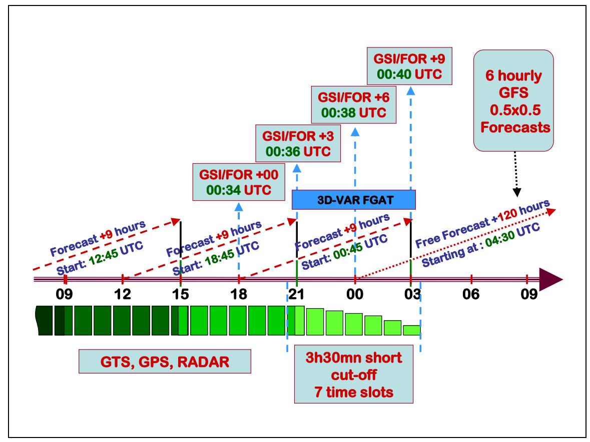

Figure 3 WRF 3D-Var warm cycling using the First Guess at Appropriate Time technique. Lateral boundary data are provided by the Global Forecasting System (GFS) analyses.

CNTRL is the control experiment, it uses the whole set of available observations with assigned tuning error factors, it takes benefit of the combined warm cycling and FGAT techniques, but only one outer loop is executed. **ITS3** is the same as CNTRL, but applies different scaling factors for background error variances and length scales at each outer loop (among a total of 3): non-linearities in the observation operators are, then, considered, and observations are quality controlled multiple times and large and small scales are correctly fitted. Table 2a and 2b give the BES tuning factors for the three outer loops. **NOERFAC** is quantifying the impact of adaptive tuning for both observation and BES on the assimilated and predicted Gonu track. **NOGPS** and **NOQSCAT** are assessing the sensitivity of Gonu to the respective contributions of GPS RO and QuickSCAT data, while **NOFGAT** informs about the advantages of FGAT. **COLD** is using GSI analyses as first guesses, it is expected to give the best track locations at least for the following reasons:

- The first guess is a final analysis, it already incorporates the complete set of actual information and it beneficiate from the technique of relocation of tropical cyclone vortices in the global first guess.

- Re-analyzing a large scale analysis (GSI), at high resolution, will enhance the accuracy of this analysis by adding small scale structures.

However, on one hand, one can not guarantee the effect of using twice the same sources of information inside the same analysis. On the other hand, the BES (CV5) must be relaxed because the quality of the analysis (taken here as first guess) is theoretically better than the quality of a 6 hours forecast (especially since, in the context of our experiments, GSI analysis and WRF first guess over d01 domain have almost the same horizontal resolution).

Table 3 *Description of the conducted warm cycling WRF 3D-Var experiments*

	CNTRL	NOERFAC	COLD	NOGPS	NOQSCAT	NOFGAT	ITS3
Observations Used	ALL	ALL	ALL	ALL except GPS RO	ALL except QuickSCAT	ALL	ALL
Observation Error factors	Yes	No	Yes	Yes	Yes	Yes	Yes
Outer loops	1	1	1	1	1	1	3
BES	CV5	CV5	CV5	CV5	CV5	CV5	CV5
Cycling	Warm	Warm	Cold	Warm	Warm	Warm	Warm
FGAT	Yes	Yes	Yes	Yes	Yes	No	Yes

Table 4 *Three sets of progressively decreasing tuning factors for variance **(a)** and length scales **(b)**, for the experiment ITS3 based on 3 outer loops.*

(a)	Outer loop 1	Outer loop 2	Outer loop 3	(b)	Outer loop 1	Outer loop 2	Outer loop 3
Stream function	1.75	1.00	0.5	Stream function	1.00	0.50	0.25
Velocity potential	1.75	1.00	0.5	Velocity potential	1.00	0.50	0.25
Unbalanced temperature	1.75	1.00	0.5	Unbalanced temperature	1.00	0.50	0.25
Specific humidity	1.00	1.00	0.5	Specific humidity	1.00	0.50	0.25
Unbalanced pressure	1.75	1.00	0.5	Unbalanced pressure	1.00	0.50	0.25

One 72 hours forecast from 04 June 2007 at 0000 UTC is initiated at the middle of each cycling experiment period after 4 days of cycling. The range of this forecast is covering the maturation stage of Gonu.

3. Actual Gonu track

On May 27, a widespread area of convection persisted over the southeastern Arabian Sea. By May 31, an organized tropical disturbance developed about 645 km south of Mumbai, India, with cyclonic convection and a well-defined mid-level circulation. The disturbance initially consisted of strong divergence along the western end of a surface trough of low pressure.

A propitious upper-air environment allowed convection to improve, and on June 1, a low-level circulation formed. It tracked westward along the southwestern periphery of a mid-level ridge over southern India. Convection continued to organize, and early on June 2, the US Navy Joint Typhoon Warning Center (JTWC) classified it Tropical depression 02A while it was located about 685 km southwest of Mumbai.

Upon first forming, the system contended with the entrainment of dry air to the northwest of the storm; this was expected to limit intensification. The storm steadily intensified to become a deep depression and a Cyclonic Storm while it was located 760 km southwest of Mumbai. As a mid-latitude trough developed over Pakistan, Gonu turned to the north and northeast, though resumed a westward track after ridging built to the north of the storm.

With a solid area of intense convection, it rapidly intensified to attain severe cyclonic status early on June 3, and with good outflow, the JTWC upgraded it to the equivalent of a Category 1 tropical cyclone. As the storm tracked under an upper-level ridge axis, outflow increased further, and combined with a local increase in ocean heat content, Gonu rapidly deepened and developed a well-defined eye in the center of convection.

Late on June 3, the storm was classified as Very Severe Cyclonic Storm Gonu, upon which it became the most intense cyclone on record in the Arabian Sea. With low amounts of vertical wind shear and favorable upper-air outflow, Gonu strengthened further to attain peak 1-min sustained winds of 130 knots and gusts to 160 knots while located about

285 km east-southeast of Masirah Island on the coast of Oman. It was upgraded to be a Super Cyclonic Storm Gonu late on June 4, with sustained winds reaching 120 knots and an estimated pressure of 920 hPa.

After maintaining peak winds for about 9 hours, Gonu was downgraded to very severe cyclonic storm status early on June 5. Its eye became cloud-filled and ragged, and the cyclone gradually weakened as it continued tracking northwestward over cooler water temperatures and through drier air. Due to land interaction with Oman, the inner core of deep convection rapidly weakened, and over a period of 24 hours the intensity decreased by 40 knots and continued to gradually decrease as Gonu interacted with land. Gonu maintained a well-defined low-level structure with a weak eye. After emerging into the Gulf of Oman, the cyclone intensified slightly. But the increasing wind shear and entrainment of dry air from the Arabian Peninsula continued to remove deep convection from its eastern semicircle.

On June 6, the cyclone turned to the north-northwest as an approaching shortwave trough, created a weakness in the ridge, and later that day the JTWC downgraded Gonu to tropical storm status and to cyclonic storm status early on June 7.

4. Experiments results.

4.1. Assimilation experiments

The different experiments were mutually compared in term of cyclone track, minimum pressure and maximum wind. The actual reference is based on a set of observed data relative to cyclone Gonu and provided by both the Indian Meteorological Department (IMD) and the US navy Joint Typhoon Warning Center (JTWC). As it could be seen on figure 5, the analyzed cyclone track is quite different in each assimilation experiment. As it was expected, the best estimated track is given by the GFS cold start assimilation experiment. The estimated location error standard deviation is about 45 km which corresponds almost to the resolution of the GSI analyses (0.5 degrees). This means that GSI analyses miss the exact track of about one grid point. ITS3 is almost comparable to GFS especially during the maturity phase of the cyclone. This experiment seems to be the best among all the other WRF warm cycling assimilations. The multiple external outer loops technique applying different calibration coefficients to the structure functions proved again its superiority (Ajjaji et al., 2007, Guo et al., 2006). CNTRL, NOERFAC, NOFGAT and NOGPS gave similar track locations especially during the cyclone initiation phase. But the performance of CNTRL, which is applying error factors, including GPS data and using FGAT technique with only one outer loop, still close to ITS3 performance with respect to the cyclone track positions. NOQSCAT is very far from the reference especially when Gonu was close to Oman coasts. The location estimation error standard deviation is more than 150 km for this latter experiment. This is denoting an obvious beneficial impact of KNMI QuickSCAT data.

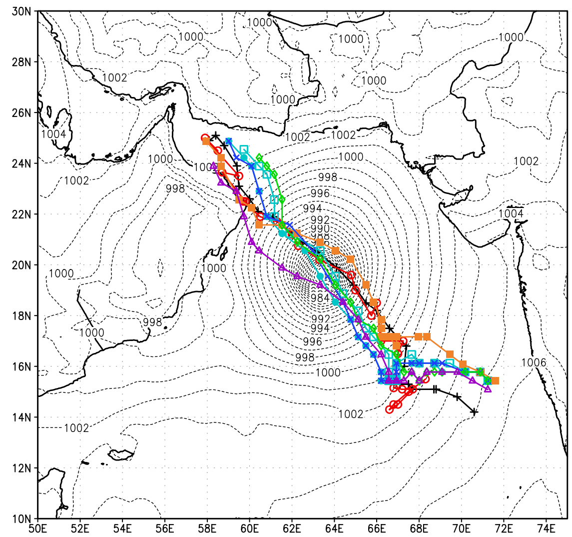

Figure 4 *Minimum pressure locations (Cyclone track) estimated by the different assimilations. Reference track given in black color, GFS in red, CNTRL in blue, NOERFAC in green, NOQSCAT in purple, NOGPS in light blue and ITS3 in orange. The isolines in the background represent the pressure field analyzed by ITS3 on 05 June at 12:00 UTC.*

Figure 6b is showing the minimum analyzed pressure in every experiment. Here, we can notice a clear limitation of the GFS analyses in quantifying accurately the minimum pressure in the cyclone eye. GFS cold start experiment extremely underestimated the minimum pressure: the deepest analyzed pressure is as low as 995 hPa, while all the WRF warm FGAT cycling assimilations estimated the minimum pressure around 955 hPa. CNTRL and NOGPS lead to the same results which are denoting a disappointing weak impact of GPS data in the context of this study, whereas one can notice the important improvement succeeded by NOERFAC and NOQSCAT when compared to CNTRL. The use of QuickSCAT data and the tuning of observations errors contributed to a deepening of about 10 hPa.

All the WRF warm cycling assimilations, except ITS3, present an abnormal characteristic when compared to the actual references: the movement of the cyclone is delayed of about 12 hours. UAE WRF forecast component is known to systematically show this behavior. Multiple eyeball verifications confirmed that UAE WRF forecasts for advective large scale systems are usually delayed of about 6 to 12 hours. In the context of this study, the first guess progressively delays the cyclonic intensity. The successive analyses relaying eventually more on the background didn't succeed in correcting this behavior. ITS3 which is applying three outer loops with different background errors statistics tuning factors, allowed the ingestion of more observations progressively. In the first outer loop background error variances are increased by a factor of 1.75 to rely more on the observations, then this factor become progressively smaller in the subsequent outer loops to fit more and more the previously updated first guess. As a result, one can notice the clear improvement contributed by ITS3 with respect to all the other

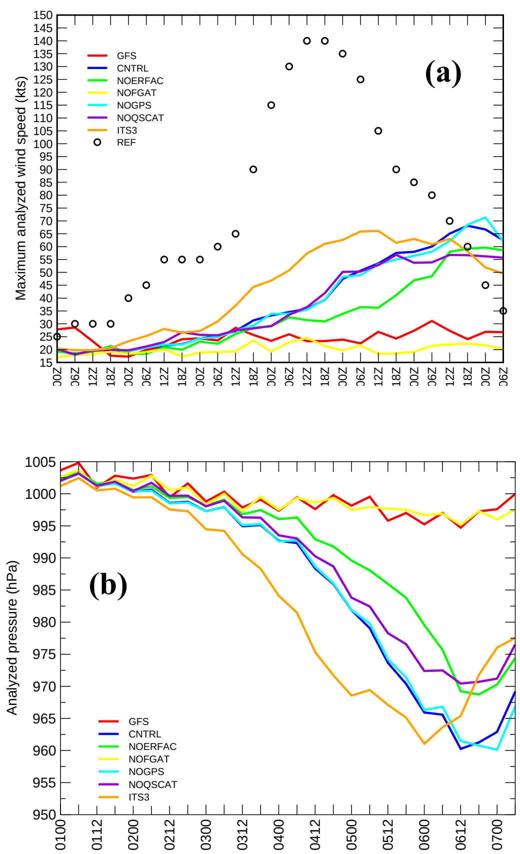

Figure 5 *Minimum pressure at the centre of the cyclone* ***(b)*** *and maximum wind speed* ***(a)*** *estimated by the different assimilation experiments.*

The wind analyses show that the maximum wind speeds were reasonably estimated by all the WRF warm assimilations except NOFGAT which remain similar to the GFS cold start experiment giving maximum winds around values not exceeding 35 knots. NOGPS shows a very small impact of GPS data, but NOQSCAT and NOERFAC show a loose of about 10 knots if QuickSCAT data were not assimilated or observation errors were not tuned. ITS3 corrects the temporal delayed locations of the maximum wind occurence of about 12 hours and thus could be considered as the most realistic assimilation.

4.2. Forecast experiments

Figure 7 is showing 66 hours forecast range of the cyclone track initiated on 04 June at 0000 UTC. At that time, almost all the analyses were showing the centre of the cyclone 20 to 50 km away from the actual position. If we take into account the spatial and temporal dimensions, ITS3 and GFS analyses were the closest to the reference state. These two analyses lead to the best track forecasts. CNTRL took an excellent trend during the first 48 hours, but oriented the track easterly during the last 18 hours forecast. NOERFAC and NOQSCAT missed clearly the track prediction. NOERFAC oriented the track wrongly strait to United Arab Emirates. NOGPS and NOFGAT (not shown) were imitating respectively almost exactly the behavior of CNTRL and GFS.

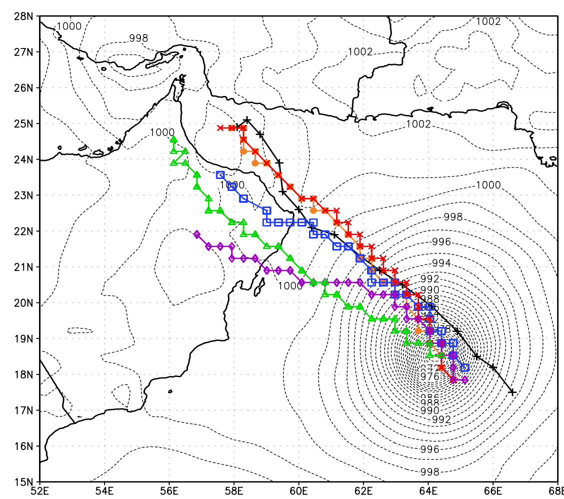

Figure 6 *Gonu Cyclone track forecasts issued from 04 June at 00:00 UTC. Reference track given in black color, GFS in red, CNTRL in blue, NOERFAC in green, NOQSCAT in purple, NOGPS in light blue and ITS3 in orange. The isolines in the background correspond to the pressure field analyzed by ITS3 on 04 June at 0000 UTC.*

In term of minimum predicted pressure and maximum predicted wind speed (Fig 8b and 8a), GFS and NOFGAT were not successful. The extreme minimum pressure and maximum wind speed predicted by GFS were respectively around 985 hPa and 35 knots, far away from the actual 920 hPa and 135 knots given by the reference and recorded on 05

June at 00:00 UTC. ITS3 predicted respectively 935 hPa and 90 knots as absolute extreme values on 05 June 12:00 UTC (12 hours after the maximum cyclone activity). It gave also a relative maximum wind value of 85 knots on 04 June at 12:00 UTC. The remaining forecast experiments delayed the maximum activity of about 24 hours, but predicted

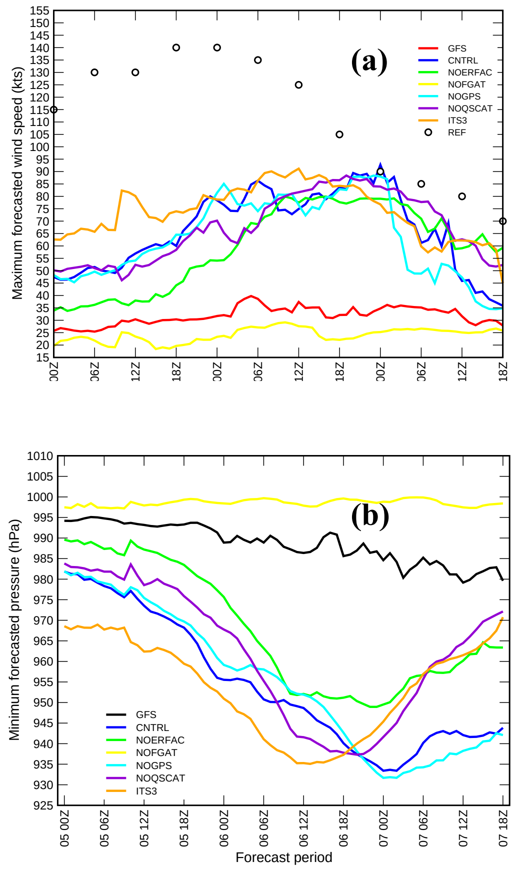

Figure 7 *Minimum pressure at the centre of the cyclone (bottom panel) and maximum wind speed (top panel) predicted by the different forecast experiments.*

5. Discussion and conclusion.

This study aimed first to document the Gonu cyclone event which succeeded unusually in affecting the north western part of the Arabian Peninsula, and second, to test the capabilities of UAE WRFVAR system in assimilating and simulating such event.

The conducted experiments quantified the impact of certain variational techniques like First Guess at Appropriate Time, Multiple outer loops and the adaptive tuning of observation errors, as well as the impact of some observational data like GPS and QuickSCAT which have the reputation of enhancing the quality of assimilating super cyclonic events.

The experiments lead to the following deductions:

- Warm WRF cycling is far better than the cold start mode. It provided, in the context of our experiments, deeper cyclone central pressure and higher accompanying wind intensity.

- FGAT technique is very efficient in following accurately the rapid evolution of cyclones characteristics. It assimilated in a satisfactory way METAR, QuickSCAT and GeoAMV data. The Degree of Freedom for Signal (DFS) (Fig 9), which measures the sensitivity of the analysis to the assimilated types of observations, is showing an important contribution of METAR and GeoAMV data.

- The technique of multiple outer loops with a progressive adjustment of background and observation errors is an excellent ingredient which extracts, in an optimal way, the information from the different sources. It leads to more consistent analyses and more accurate track forecast. But each extra outer loop is equivalent to one analysis run in term of execution time.

- GPS refractivities didn't impact significantly the analyses and the subsequent forecasts unlike QuickSCAT data which contributed in much improved analyses and forecasts quality. GPS data failure is likely due to their reduced density both in space and time, and eventually also, to their misplacement with respect to the actual cyclone positions.

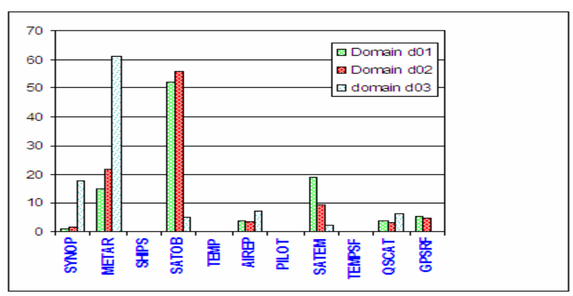

Figure 8 *Degree of Freedom for Signal (DFS) obtained for the assimilated observational data in the context of the conducted experiments.*

UAE WRF/WRFVAR simulated successfully the super cyclone Gonu. The tunings made during this case study are included in the U.A.E. operational suite. This study was also an opportunity to document the Gonu event. It could be extended to the assessment of the prospected new techniques and type of observation in the future WRFVAR releases such as Ensemble Transform Kalman Filter technique, digital filters as a weak constraint, and raw radiances assimilation.

6. Acknowledgment.

This work was supported by the United Arab Emirates Air Force and Air Defense and the United Nations Development Programme. The authors are grateful for NCAR WRFVAR team and for the KNMI Scaterrometer project which provided the QuickSCAT data and the related support.

7. References.

Ajjaji, R., Al-Katheri, A. A., 2007: Automatic two-way nested WRF Middle-East numerical forecast application. WRF Users' Workshop June 14 - 18, 2007. Boulder, CO.

Barker D. M., Y.-R. Guo, W. Huang, H. Huang, S. Rizvi, Q. Xiao, and M.-S. Lee, 2005: WRF-VAR A Unified 4/4D-Var Data Assimilation system for WRF. Preprints. 6th WRF/MM5 Users Workshop. NCAR. Boulder, CO.

Courtier, P., J.-N. Thépaut and A. Hollingsworth, 1994 : A strategy for operational implementation of 4D-Var using an incremental approach. Q. J.R. Meteorol. Soc., 120, 1367-1387

Chapnik. B., G. Desroziers, F.Rabier and O.Talagrand. 2004, Properties and first applications of an error statistic tuning method in variationnal assimilation. Quart. J. Roy. Meteor. Soc., 130, no. 601, pp. 2253-2275

Desroziers, G. and S., Ivanov. 2001, Diagnosis and adaptive tuning of information error parameters in a variational assimilation. Quart. J. Roy. Meteor. Soc., 127, 1433-1452

Gu JF, Xiao QN, Kuo YH, et al. Assimilation and simulation of typhoon Rusa (2002) using the WRF system. Advances in Atmospheric Sciences, 2005, Vol 22 (3), 415-427

Guo, Y.-R., H. Kusaka, D. M. Barker, Y.-H. Kuo, and A. Crook, 2005: Impact of Ground-based GPS PW and MM5-3Dvar Background Error Statistics on Forecast of a Convective Case. SOLA, Vol. 1, 073-076, doi: 10.2151/sola.

Guo, Y.-R., H.-C. Lin, X. X. Ma, X.-Y. Huang, C.T. Terng, and Y.-H. Kuo, 2006: Impact of WRF-Var (3Dvar) Background Error Statistics on Typhoon analysis and Forecast. WRF users workshop, Boulder, Colorado, 19-22 June 2006.

Kain, J.S., and J.M. Fritsch, 1993: Convective parameterization for mesoscale models: The Kain-Fritsch scheme. The Representation of Cumulus in numerical models, Meteor. Monogr., 46, Amer. Meteor., Soc., 165-177.

Lee M.-S., D. M. Barker, W. Huang, and Y.-H. Kuo, 2004: First Guess at Appropriate Time (FGAT) with WRF 3DVAR. Preprints. 5th WRF/MM5 Users Workshop. NCAR. Boulder, CO.

Skamarock, W. C., J. B. Klemp, J. Dudhia, D. O. Gill, D. M. Barker, W. Wang, and J.G. Powers, 2005: A Description of the Advanced Research WRF Version 2. NCAR/TN-468+STR, 88 pp.

Wee, T-K., and Y.-H. Kuo, 2004: Impact of a digital filter as a weak constraint in MM5 4DVAR: An observing system simulation experiment. Mon. Wea. Rev., 132, 543-559.

Wu, W.-S., R. J. Purser, and D. F. Parrish, Zou, X., and Q. Xiao, 2000: Studies on the Initialization and Simulation of a Mature Hurricane Using a Variational Bogus Data Assimilation Scheme. J. Atnos. Sci., 57, 836-860.

Parrish, D. F., and J. Derber, 1992: The National Meteorological Center’s spectral statistical interpolation analysis system. Mon. Wea. Rev., 120, 1747–1763

Veerse, F., and J.-N. Thépaut, 1998: Multiple-truncation incremental approach for four-dimensional variational data assimilation. Q.J.R.Meteorol. Soc., 124, pp 1889-1908.