Detection and Tracking of Tropical Cyclones on a Seasonal Scale in the Philippines

Josefina C. Argete[1*] and Raquel V. Francisco[2]
[1]Associate Professor
Institute of Environmental Science and Meteorology
College of Science, University of the Philippines
1101 Diliman, Quezon City, Philippines
E-mail: argetej@yahoo.com
[2]Scientist I, PAGASA-DOST
Date received: May 11, 2006; Date accepted: April 19, 2007

ABSTRACT

A regional climate model is used to detect tropical cyclones (TC) and simulate their tracks for a four-month (June-July-August-September) wet season in the Philippine region. The model, run at 45-km resolution, is forced along the boundaries with 6-hourly reanalyses data (ERA-40 with about 250-km resolution). Three experiments are devised which varied the size of the domain and placement of the boundaries

A detection and tracking algorithm is developed using 850-mb vorticity threshold, minimum sea level pressure and the presence of a warm core aloft as criteria. The tracks extracted from the ERA-40 field, herein called analyses track, are compared with JTWC best track to test the performance of the tracking algorithm. Of the fourteen (14) TC that entered the domain, ten were formed in the Pacific Ocean and four in the South China Sea. The algorithm detected all TC and skillfully captured the JTWC best track. From the 417 cases (6-hourly positions of the 14 TC), the mean zonal and meridional errors are -164, -23 km, respectively, where the analyses tracks are on the average moving faster westward and southward than the best track. The relatively small magnitude of errors indicates skill of the tracking method.

The regional model is able to detect all 14 TC but with tracks that are farther displaced north of analyses. Simulation of track was enhanced as domain size is decreased. The intensity simulation is improved as more typhoons otherwise not found in the forcing data are generated by the regional model. This study demonstrates that a regional model forced by "perfect" boundary conditions can reasonably simulate the tracks and intensity of tropical cyclones on a seasonal scale. The importance of the use of the proper domain configuration is also shown.

Keywords: regional climate modeling, tropical cyclone tracks

*Corresponding author

INTRODUCTION

The Northwest Pacific basin spawns the maximum number of tropical cyclones (TC) globally, about 35 per year. The typical track of these TC is northwestward, with about 20 passing the Philippine area of responsibility (PAR). Because the Philippines lies right in the path of TC, reports of staggering damage to life and property due to this natural disaster is an annual event. As a mitigating measure, accurate forecasting of track and intensity is given the highest priority. These are derived as short-range (3-5 day) forecasts from mesoscale models. Seasonal or climate forecasts, on the other hand, are predictions on the time scale of months. These are very important for medium-range planning in government and industry. For instance, it is observed that the frequency, tracks and intensity of TC are influenced by the warm (El Nino) and cold (La Nina) phases of the ENSO the consequences of which impact on crop production, water supply and even the incidence of pests and diseases. Empirically-based (statistical analyses of past data) methods search for predictors such as SST and other Nino indices and are limited to stating that TC expected in the next season are higher or lower than normal (Chan et al, 2001).

Dynamical forecasts of TC activity are produced at major weather centers running global circulation models (GCM). Because of its global scope, however, the resolution is low (Bengtsson et al, 1995). Furthermore, GCM run on mainframes. Local research institutions in developing / transitioning economies do not have the computational capacity at present to run GCM, and yet there is a pressing need for them to improve regional forecasting capacity using currently viable methods. An economical solution for improving the resolution is to nest a regional climate model within a global model. In this scheme, the regional model which is configured to run on a personal computer is forced at the boundaries by the global model outputs for the region which may be requested from centers running GCM. The cyclones produced by the regional models have been found to be weaker than observed but are more realistic than the vortices generated by GCM (Walsh and Waterson, 1997; Nguyen and Walsh, 2001; Vitart et al, 2003; Landman et al, 2005).

GCMs are able to create tropical vortices similar to tropical cyclones. The coarse resolution however leads to lack of the presence of the eye and eyewall and are weaker than observed (Bengtsson et al, 1995) which then influence the simulated intensity and track. The mean number of tropical storms simulated by GCM is only about ½ the number observed. Different GCMs showed variabilities but in general the tracks were found to be located too far to the east over the Indian Ocean (Vitart et al, 1997) and the western North Pacific (Camargo and Zebiak, 2002a).

As mentioned, an alternative and economical solution for improving the resolution is to nest a regional climate model within a global model. The basic question of whether regional climate models can generate meaningful small-scale features that are absent in the initial and boundary conditions supplied by global models has often been asked. Some argue that predictability is limited by turbulence (de Elia and Laprise, 2002). It would be too optimistic to say that the formation and movement of a mesoscale system such as a tropical cyclone which are defined by synoptic conditions which have a predictability of a few days at most can be predicted months in advance. However, tropical cyclones are also influenced by large-scale flow. And since large-scale fields of the atmosphere are predictable on a seasonal scale, these can be "downscaled" using regional climate models.

Regional model runs over the southwestern Indian Ocean (Landman, et al, 2005) and Australian region (Walsh and Waterson, 1997) simulated more realistic vortices but found the TC to weaken faster than observed in their westward track. Experiments on the proper choice of domain size and the positioning of the lateral boundaries for the regional model improved their results in capturing the life cycle of TC. The domain must be large enough to encompass the large-scale atmospheric fields provided at the boundaries that are relevant to tropical cyclone formation and movement and allow model internal processes to develop with minimal constraints from the boundaries (Seth and Giorgi, 1998, Landman et al 2005).

In this study, the performance of a regional climate model in detecting and tracking tropical cyclones for a four-month (JJAS) wet season period in the Philippine region is investigated. The 2005 version of RegCM3 is used, details of which are presented in Section IIA. The model is forced along the lateral boundaries with time-dependent reanalyses data with about 250-km resolution. The use of reanalyses data allows evaluation of the regional model performance given "perfect" boundary conditions. A detection and tracking algorithm is developed using meteorological variables discussed in Section IIC. The skill of the algorithm is tested by comparing the tracks extracted from reanalyses with the best track data of JTWC. Three model experiments are devised by varying the domain size and placement of lateral boundaries. Model tracks are then compared with reanalyses tracks. Finally, the influence of domain size in simulating tropical cyclone intensity is assessed.

MATERIALS AND METHODS

A. The regional climate model

The International Centre for Theoretical Physics (ICTP) Regional Climate Model version released in February 2005 and herein called RegCM3 is used in this study. It was developed at the National Center for Atmospheric Research (NCAR) and described in detail by Giorgi et al (1993, a,b). The dynamical component is essentially the same as the standard Pennsylvania State University Mesoscale Model (MM4). Since then, as new physics schemes have become available, refinements were done on the model.

It is a hydrostatic, compressible, primitive equation, terrain following sigma coordinate model with 18 vertical levels. Since the domain is not of a global nature, the lateral boundaries require periodic forcing. A one-way nesting technique (Giorgi et al, 1994) uses ECMWF reanalyses (ERA-40) meteorological fields as driving initial and time-dependent lateral conditions, with sea surface temperature (SST) data used as surface boundary condition.

The RegCM3 model is composed of four components: terrain, initial and boundary conditions (ICBC), RegCM (main program) and postprocessor. Terrain and ICBC are the two components of the preprocessor. Terrain information was obtained from an elevation dataset of the US Geological Survey at 3-min resolution (USGS GTOPO30_3min). The land use information is taken from the global land cover characterization of vegetation or land cover at 3-min resolution (USGS GLCC_3min). The initial and boundary condition datasets for the ICBC were obtained from ERA-40, a 40-yr (up to 2002) 6-hourly 2.5^o resolution global reanalyses of atmospheric fields. Surface boundary information is obtained from weekly optimal interpolation sea surface temperature (OISST) data at 1o resolution. The datasets were requested from ICTP (http://ictp.trieste.it/~pubregcm).

B. Model experiments

The simulation of TC tracks was performed on three domains shown in Fig.1. The largest domain (designated as D1) consists of 148 grids along x and 85 grids along y and covers the area 100^{o}E to 160^{o}E and 0^o to 33^{o}N. The eastern boundary is placed at 160^{o}E to capture the area of maximum TC genesis for storms affecting the Philippines (Elsberry et al, 1987). The eastern

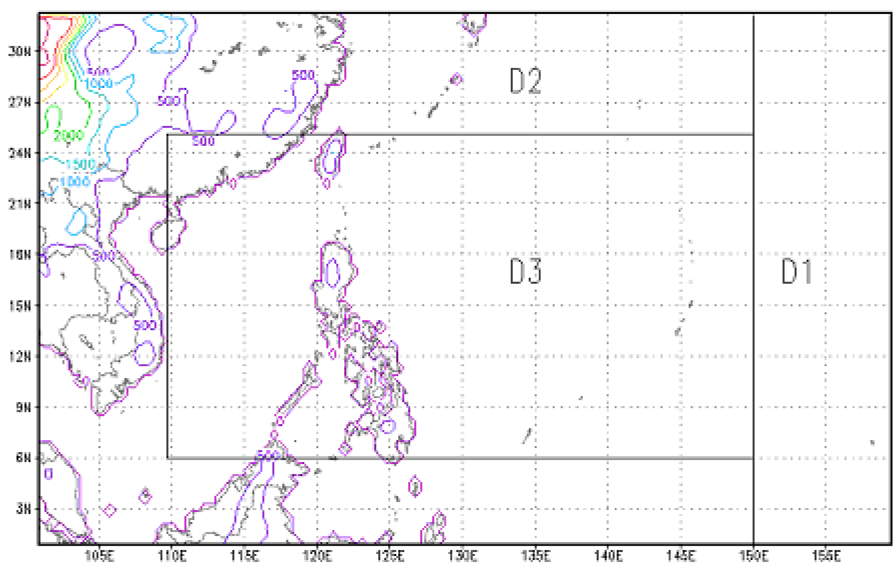


Fig. 1. The regional model domains (labeled D1, D2 and D3). D1 is the largest while D2 is 10 longitude degrees smaller than D1. The smallest domain D3 is embedded within D1 and D2. The topography is represented as height contours in meters.

boundary is then moved westward to 150°E , with the other three boundaries unchanged, to create a smaller domain D2 with 122 grids along x and 85 grids along y. The smaller third domain D3 with 98 grids along x and 51 grids along y is embedded within D1 and D2. The horizontal resolution for all experiments is set at 45 km at a time step of 120 s. Each model run is initialized on May 25, 1996 and allowed to proceed until October 1, 1996, with the first 6 days of integration discarded to allow for model spin-up. The 6-hourly model outputs of atmospheric fields therefore cover the June-July-August -September (JJAS) TC season in 1996 in the Philippine region.

C. Tracking TC

The detection and tracking algorithm is based on methods described in three papers (Walsh and Waterson,(1997), Vitart (1997) and Camargo (2002)). These methods have similarities as well as differences. The similarities are basically on the use of certain criteria in determining whether a vortex is considered a model storm. These criteria were found to be basin-dependent. In Camargo and Zebiak (2002), they used a detection and tracking algorithm which applies basin-dependent threshold criteria to low-level vorticity, surface wind speed and vertically integrated temperature anomaly to determine the position of the storms every 6 hrs. The tracking algorithm was applied to an ensemble of general circulation models. In Vitart (1997), differences with those of Camargo (2002) are the inclusion of minimum sea level pressure as detection parameter and a different approach in determining the warm core aloft. In Walsh (1977), the three detection criteria are 850-mb vorticity maximum, the warm core aloft and the 10-m windspeed.

Detection and tracking algorithm

The following description of the detection method is largely based on the work of Vitart (1997). The algorithm first locates the position of intense vortices with a warm core for the initial time step as follows:

1. Locate the local maximum of relative vorticity greater than $3.6 \times 10^{-5}\ s^{-1}$ at 850 mb. This is the low-level vorticity threshold of Camargo for the West North Pacific Basin. Here relative vorticity ζ is defined as

$$\zeta = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \qquad (3.1)$$

   The center of vorticity is manually located on the vorticity map of the RegCM3 (hereafter referred to as model vorticity) on the date of the first day of a storm. This first day of storm is based on the observed best track data of JTWC*. For example, one JTWC storm starts on June 19 and ends July 27. The model vorticity on June 19 is displayed and the cursor is pointed at the center of vorticity close to the coordinates observed by JTWC. This gives the initial coordinates of the model storm.

2. Locate the minimum sea level pressure as the center of the storm. Define a box (10 x 10 grids) centered around the model maximum vorticity. The coordinates of the minimum sea level pressure within the box is now defined as the center of the model storm.

3. Test whether the model storm has a warm core aloft.

* Define a box 8° x 8° (lat x lon) centered at the storm center between 200 and 500 mb and determine the volume-average temperature (T_{ave})
* Define a box 2° x 2° centered at the storm center between 200 and 500 mb and calculate the anomalous temperature per grid ($T_{anom} = T - T_{ave}$)
* Get the coordinates of the center of the maximum T_{anom} . This is the center of the warm core.
* From the center of the warm core, the temperature must decrease by at least 0.5°C in all directions within the 8° x 8° box.
* Test whether the center of the warm core and the center of the storm are within 2-degrees (lat/lon) of each other. If the warm core is too far from the storm center, it is not considered a model storm.

*best-track dataset for Northwest Pacific Ocean. This is a past analysis of typhoons provided by the Joint Typhoon Warning Typhoon Centre (JTWC), Hawaii. http://www.npmoc.navy.mil

The above criteria must be satisfied to define a model storm. After the initial storm center is located, the 6-h track of the storm is tracked as follows:

4. Test if on the next time step, there are storms within 800 km of the previous storm's center. If there is none, the trajectory is stopped. Otherwise, the storm in the present time step must belong to the trajectory of the initial storm. In the West North Pacific where more than one storm may occur within 800 km of each other, preference is given to the storms located in the northwestern quadrant.

5. The algorithm is run for the duration of the storm as observed by JTWC or when the storm crosses the domain boundaries. The algorithm outputs the date of analysis, the coordinates of the storm center, and the wind speed. The model and JTWC trajectories are then plotted and compared.

D. Validating model tracks

The difference between model and observed tracks is measured as displacement error. This is defined as the distance between the forecast (x_f, y_f) position and the observed (x_o, y_o) position of the storm, x and y being longitude and latitude, respectively. The displacement error (E) in km is estimated from the zonal (E_z) and meridional (E_m) errors:

$$E_z = (x_f - x_o)\ \cos\left(\frac{y_f + y_o}{2}\right) \qquad (3.2)$$

$$E_m = (y_f - y_o) \qquad (3.3)$$

$$E = (E_z{}^2 + E_m{}^2)^{1/2} \qquad (3.4)$$

A positive E_z indicates a forecast track that is moving slower than the observed track in the westward migration. A positive E_m means that the forecast track is north of the observed position.

RESULTS AND DISCUSSION

A. Assessment of the tracking algorithm

The detection and tracking method is tested on ERA-40 data interpolated to the same horizontal resolution as the model grid. The resulting 6-h tracks for each TC, herein called the analyses tracks, are then compared with the 6-h JTWC tracks. It is to be noted that while both data sets (ERA-40 and JTWC) are derived from observations, a disparity is expected because the nature and the manner by which they are produced are very different. JTWC best tracks are post-analyzed tracks and are point estimates of minimum sea level pressure and maximum sustained winds. ERA-40 is a description of the large-scale atmospheric fields at a coarser resolution. It is a global analysis of atmospheric circulation produced by three-dimensional variational (3-Dvar) 6-hourly data assimilation of an atmospheric model for 45 years from 1957 to 2002 (Kallberg et al, 2005). It was produced to foster international research by making observations and analyses widely available. The ERA-40 data product available from ECMWF public Data Server and used in this study has 2.5^o resolution. Here, gridded atmospheric variables u, v, T, p and q at 23 pressure levels and 2.5-degree (about 255 km) horizontal resolution are regridded to 45 km within the domain. Using this "observed" gridded data, the tracking algorithm is applied over the domain to produce the analyses tracks. This comparison of tracks aims to calibrate the tracking algorithm. The difference in 6-hourly positions of the analyses and JTWC tracks expressed as zonal and meridional errors is considered a measure of the performance of the tracking algorithm. If the tracking algorithm has skill, the analyses tracks should capture the JTWC best tracks. A divergence of the two tracks may in part be due to the inherent difference of the two data sets as mentioned above but for lack of basis in quantifying this, the error obtained is attributed to the performance of the tracking algorithm. The calibration thus accounts for two sources of error - the inherent difference between ERA-40 and JTWC datasets and the limitations of the tracking algorithm - the sum of which is considered a measure of the skill of the tracking.

TC Number and Date		E_z	E_m	E	Remarks
1.	jul 11-17 1996	-476	99	592	Pac
2.	jul 19-27 1996	-27	39	179	Pac
3.	jul 19-25 1996	24	7	140	SCS
4.	jul 24-31 1996	1	-32	145	Pac
5.	jul 27-31 1996	-1119	37	1233	Pac / Twins with TC#4
6.	aug 01-14 1996	-17	-32	160	Pac
7.	aug 04-07 1996	110	47	226	SCS
8.	aug 11-16 1996	146	-38	195	SCS
9.	aug 14-23 1996	10	-130	262	Pac
10.	sep 02-10 1996	169	-189	285	Pac
11.	sep 06-14 1996	-1199	175	1285	Pac / Twins with TC#10
12.	sep 09-23 1996	-173	-87	273	Pac
13.	sep 16-23 1996	67	-13	141	SCS
14.	sep 22-30 1996	-19	-81	178	Pac
Weighted average		-164	-23	378	
Std deviation		514	241	476	

Table 1
Zonal (Ez), meridional (Em) and displacement error (E) in km of ERA-40 track referenced against JTWC best track

Based on the JTWC tracks, a total of 14 TC entered the largest domain in JJAS 1996: 0 in June, 5 in July, 4 in August and 5 in September. These are numbered 1 to 14 in Table 1. The 6-h JTWC and analyses tracks for 5 selected TC are shown in Fig 2 (a-e). Each TC is identified by the time (yyyymmddhh) it first attained tropical depression stage according to JTWC data. A TC is classified as a tropical depression when the maximum sustained wind near the center (u_{max}) is less than 17 m/s, a tropical storm when u_{max} is between 17 and 33 m/s and a typhoon when u_{max} is greater than 33 m/s.

Of the 14 TC that entered the domain, 10 were formed in the Pacific Ocean (Pac) and 4 in the South China Sea (SCS). The algorithm was able to detect and track all the 14 TC in the ERA-40 fields. The 5 cases shown in Fig. 2 are chosen to represent two cases for storms that formed in the Pacific Ocean (Fig 2a and Fig 2c), two from the South China Sea (Fig. 2b and Fig. 2e) and one for a case when two storms exist at a distance close enough to cause interaction for a given time period (Fig. 2d). It is to be noted that the JTWC best tracks are skillfully simulated by the tracking algorithm regardless of the TC's area of genesis, except for two cases (represented as TC #5 and #11 in Table 1) one of which is shown in Fig 2d. Here, the analyses track of TC with duration July 27-31 (TC #5) diverged from the JTWC track and followed closely the track of TC in Fig. 2c with duration July 24-31 (TC #4). With this case of having twin storms (or pairs) in a region, it is seen that the algorithm may have to be improved in the proper control of identifying which TC is to be tracked. The same situation of having storm pairs is seen in another case (not shown) wherein TC with duration September 6-14 (TC #11) interacts with the tracks of TC on September 2-10 (TC #10).

The errors in terms of differences between analyses and best track are shown in Table 1. The errors are calculated using Eqn 3.2 - 3.4 with ERA-40 as the forecast position and JTWC as the observed position. Negative values of the zonal and meridional errors indicate that the analyses tracks are on the average moving faster westward and southward than the best track. The errors are (weighted) averaged over the corresponding 6-h positions. The largest errors are incurred for the two cases with storms (twins) whose tracks approach each other during a certain period in their duration. These are TC #5 and TC #11. From the 417 counts of 6 h positions for the 14 TC, the mean displacement error is about 378 km. A scatterplot of the zonal and meridional errors for the 417 cases is shown in Fig. 3. Based on the mean zonal (-164 km) and meridional (-23 km) errors, the analyses tracks are biased towards the left (fast to the west) and south of

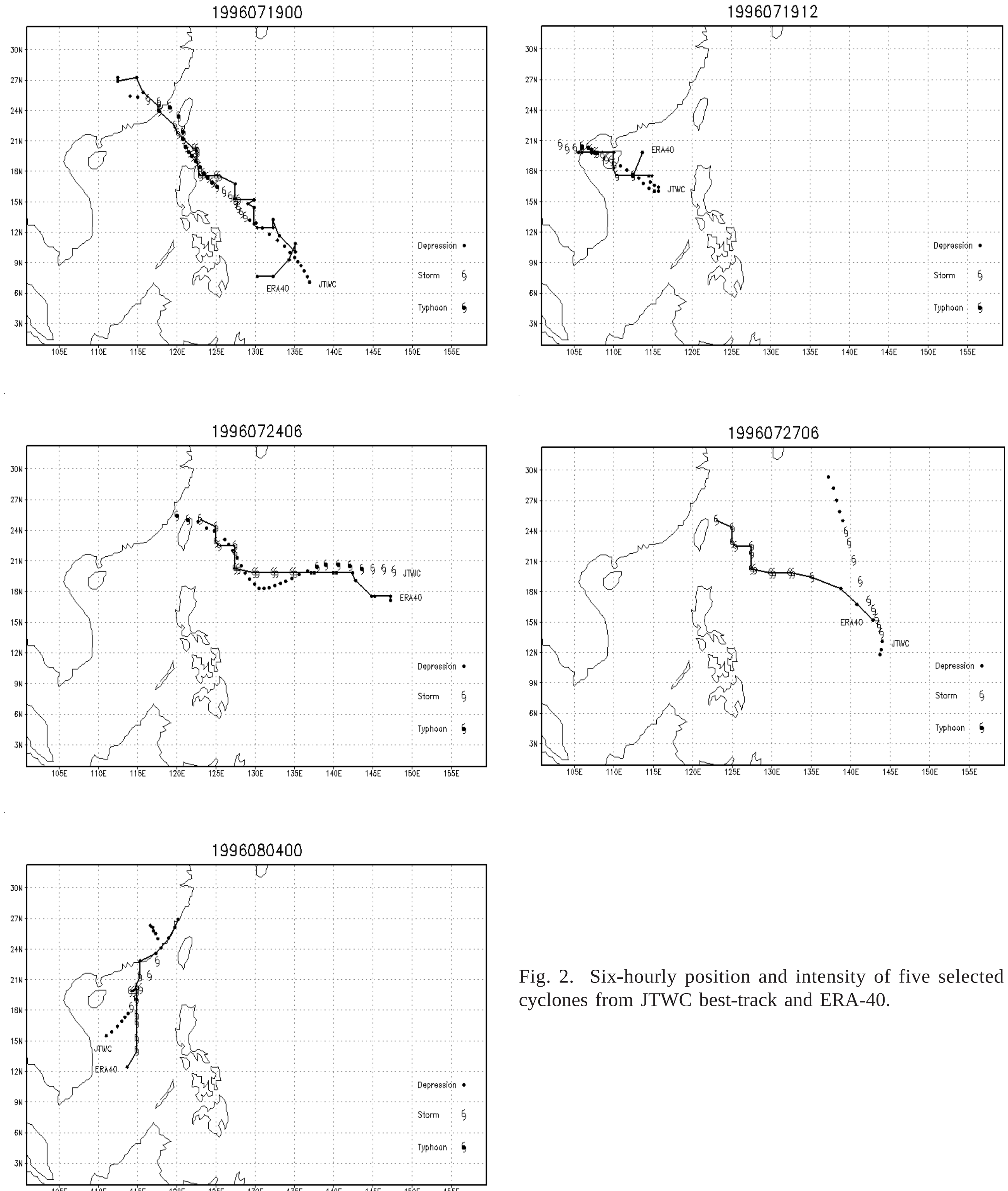


Fig. 2. Six-hourly position and intensity of five selected cyclones from JTWC best-track and ERA-40.

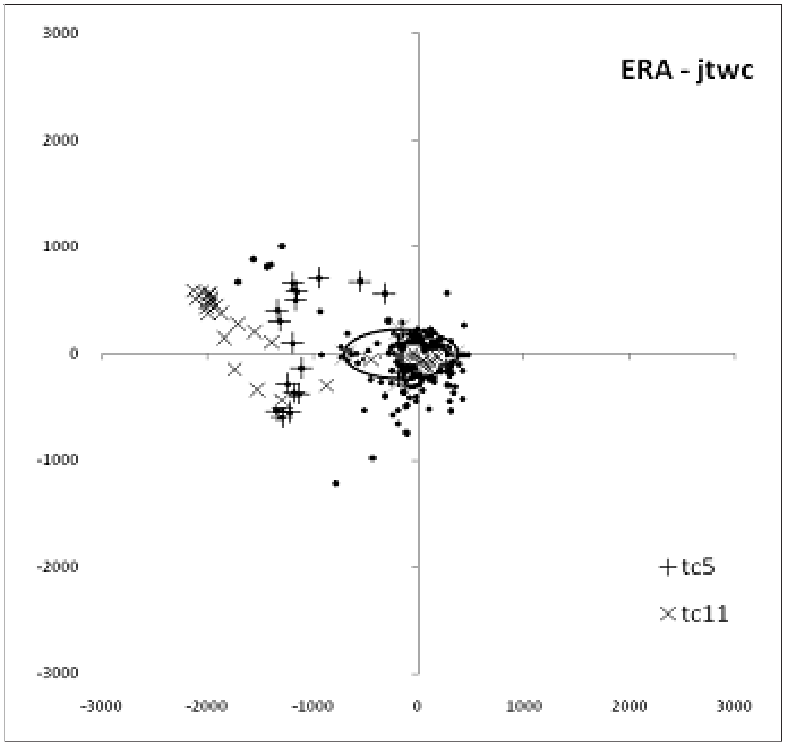


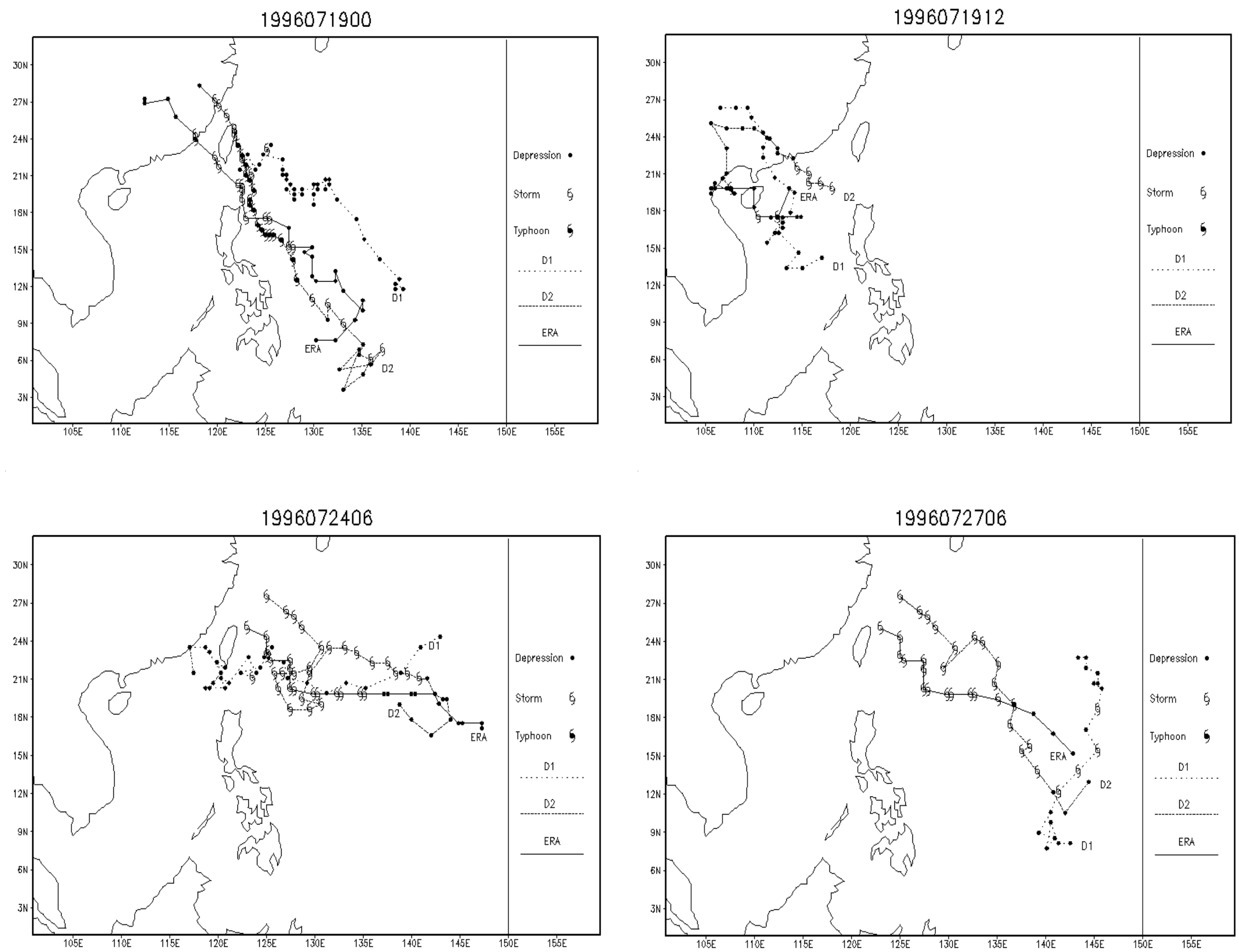
Fig. 3. Six-hourly zonal (x-axis) and meridional (y-axis) errors of analyses tracks referenced against JTWC tracks. The ellipse indicates position errors of 1 standard deviation centered on the mean.

the best track position. The ellipse in the figure, centered on (-164, -23) indicates the range of the zonal and meridional errors which accounts for 68% of the population, or 1 standard deviation. The bias is largely due to the twin storms TC #5 and TC #11. If the two cases having twin or interacting storms are excluded, the zonal and meridional errors are drastically reduced to 15 and 34 km, respectively, where the analyses tracks are slightly east and northward of the JTWC track. With a 45-km grid size, the average errors translate to 0.3 and 0.8 grid displacements from the JTWC track. This is a relatively small magnitude of error. However, twin storms often occur in the NW Pacific basin and excluding them from analysis is not appropriate. For this calibration, a zonal error of -678 km (mean +/- 1s) or (-164 - 514) and meridional error of -264 km (-23 - 241) are established. These errors are of the same order of magnitude as that found by Camargo and Sobel (2003) on the eastward bias of ECHAM4.5 with 2.50 horizontal resolution. They note that while the 2000 km zonal displacement may seem large, it is not significantly greater than the horizontal extent of a typical TC and is therefore modest from a dynamical point of view.

Given the competent performance of the tracking, the same algorithm is used in the subsequent tracking of TC simulated by the regional model. The question now to be addressed is whether the regional model if fed by 6-h ERA-40 fields at the lateral boundaries is able to simulate the atmospheric variables in the domain that define a tropical cyclone. If the model simulates the ERA-40 fields, then the errors between model and ERA-40 tracks should be minimal, or of similar order of magnitude as the errors used in the calibration phase. Errors much larger than these may be attributed to limitations of the regional model.

B. Effect of domain size on model tracks

The model and analyses tracks are compared in Fig. 4(a-e) for the same 5 selected storms in Fig.2(a-e). The regional model detected and tracked all the 14 TC that are observed in the ERA-40 fields but only 5 representative cases are shown. The large domain D1 extends to 160^{o}E while D2 covers up to 150^{o}E, 10 degrees shorter. The tracks for domain D3 are not shown in this paper for the main reason that they cause



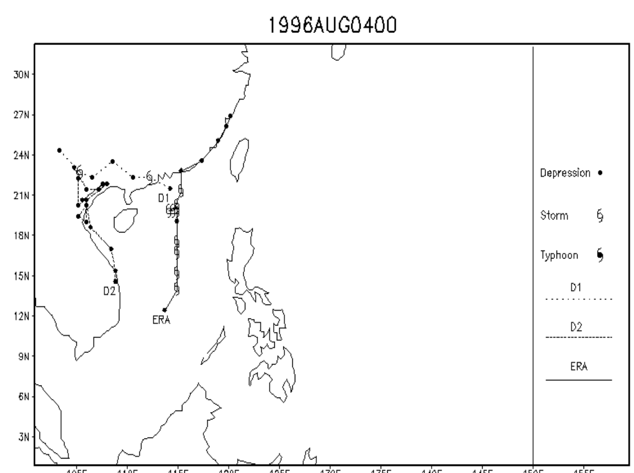


Fig. 4. Model track and intensity for domains D1 and D2 for 5 selected cyclones. The reference ERA-40 track and intensity are also shown.

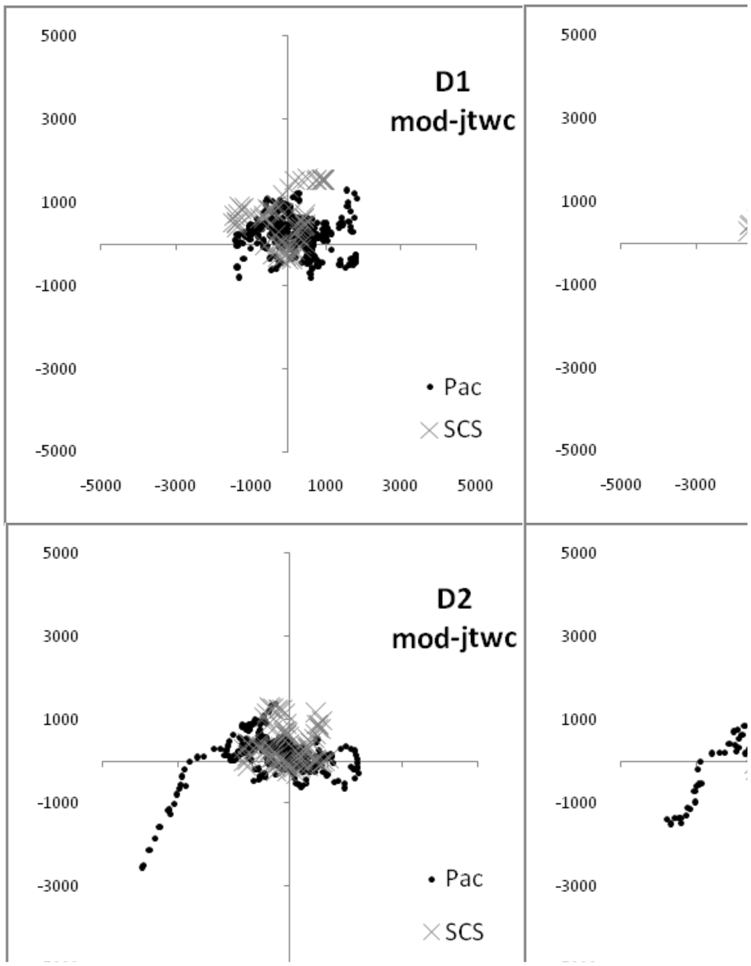


Fig 5. Six-hourly zonal (x-axis) and meridional (y-axis) errors of model tracks referenced against JTWC (left) and ERA-40 (right) for the three domains. The basins of TC origin (Pacific Ocean and South China Sea) are also indicated.

unnecessary clutter in the TC track diagrams. However, the summary for the D3 experiments are mentioned to reinforce the conclusions drawn on the influence of domain size on TC track and intensity simulation. The date above each figure denotes the time the TC became a tropical depression as reported by JTWC.

The 6-h zonal and meridional errors of the model tracks referenced against JTWC best track (mod-jtwc) and ERA-40 (mod-era) track are shown as scatter plots in Fig.5. The errors from TC that developed in the Pacific Ocean (Pac) and South China Sea (SCS) are also indicated. For all domain sizes, the model is able to capture the TC tracks regardless of its basin of origin but the magnitude of errors is larger for Pacific TC. TC coming from the Pacific travel over a wide expanse of ocean, have longer tracks and are reportedly easier to track. TC in the SCS are historically difficult to forecast due to the short erratic tracks, slow movement and the complicating influence of topography during landfall. The small zonal error may be due to the smaller spatial area covered by the SCS storms. This also suggests the sensitivity of the model to topography. The large displacement of the model tracks from observations as seen in D2 is again due to the presence of twin TC in the Pacific Ocean. This is evident in Fig. 4d for TC#5. The best track for TC#5 (shown in Fig. 2d) is better captured by the model in the large domain D1 than in D2. The main difference between D1 and D2 is the position of the eastern part of the domains. For TC#5 which developed close to the eastern boundary of D2, boundary effects may have influenced the simulation of the TC. The tracking method is also a source of error. Since the location of the warm core is determined from the volume-averaged temperature of a box of size 8^0 centered on the TC and the location of the TC center is determined from the minimum sea level pressure in a box 0f 10 grids, a TC very close to the boundary may have an erroneously determined warm core and TC center position.

A comparison of the zonal and meridional errors among analyses tracks and model tracks at three domain sizes is summarized in Table 2 and presented as scatter plots in Fig. 6. As was done for Fig. 3, the ellipses represent the spread within 1 standard deviation from the mean zonal and meridional error. The errors from analyses tracks are shown in bold. Of the four ellipses, that of the analyses tracks is the smallest because the errors here are derived from a comparison of two observed data sets. In this calibration step, the errors are considered to arise from the inherent difference of the

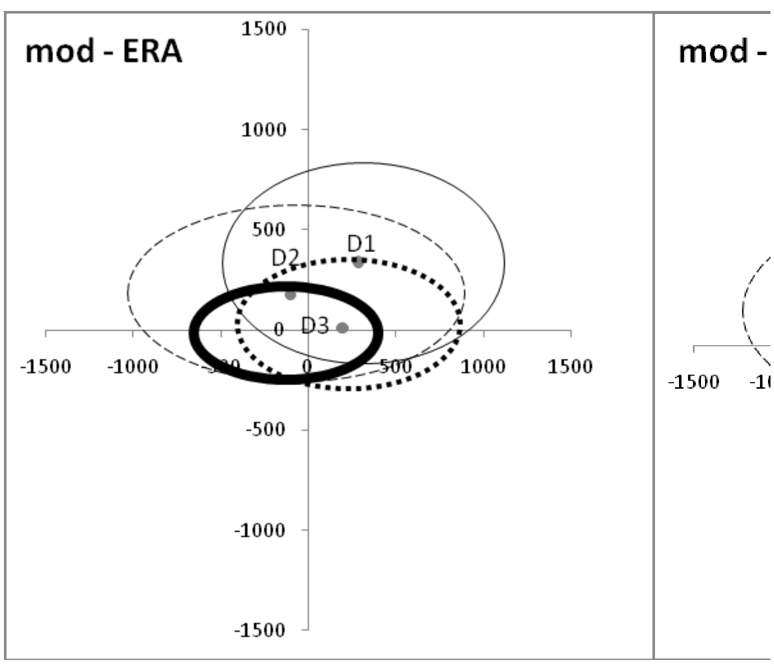


Fig. 6. Positions of the mean zonal and meridional errors of the model tracks relative to ERA-40 (left) and JTWC (right) for the three domains. The corresponding ellipses of 1 standard deviation centered on the means are also shown (D1 solid, D2 dashed and D3 dotted). Bold solid ellipse represents that of the analyses tracks shown in Fig.3.

	Mean		Std Dev	
	Ez	Em	Ez	Em
Analyses	-164	-23	514	240
D1	125	307	731	463
D2	-249	157	972	485
D3	-19	9	503	309

Table 2. Zonal and meridional errors of analyses tracks and model tracks at varying domain sizes.

data sets and on the skill of the tracking algorithm. The other three ellipses are measures of the errors due to the regional model, the tracking method and the bias between data sets combined. The differences of the means of the four ellipses were found to be statistically significant at 1% using a standard t-test, except for the zonal errors of D2 and analyses and meridional errors of D3 and analyses, which were significantly different at 10% probability level. The shape of the ellipses indicates larger east-west errors.

The model errors are smallest for the small domain D3. This is expected since error growth for small domains is constrained by the boundaries. A regional model forced with reanalyses at the boundaries gives a better hindcast simulation for a smaller domain (Chouinard et al, 1994). The use of a very small domain results to small errors because the tracks are artificially controlled by the boundaries and the model physics are not allowed to develop. A very small domain however misses some TC that may be important for the region. For this case, 4 TC whose tracks were outside the domain but whose influence was felt in the Philippines were missed. Increasing the domain size from D3 to D1 led to tracks that are displaced northwards (Em positive). The westward bias of model tracks in D2 is in part due to TC#5 which developed very close to the eastern boundary of D2 and to the twin storms TC#5 and TC#11 which were not properly identified by the tracking algorithm. Basing largely on the standard deviation, D1 is considered the optimal domain configuration in this study. The size and placement of D1 allow the capture of the most number of TC affecting the Philippine region, avoid the constraints of boundaries and minimize propagation of errors.

When a very large domain is used (not done here), it is possible that the model physics is not sufficient to generate a vortex on its own. It is also possible that even with "perfect" model physics, the vortex remains weak because of the limitations imposed by chaos (Landman et al, 2005). These issues cannot be settled in this study since many sensitivity studies on the internal variability of the model need be done and are beyond the scope of this work.

C. Effect of domain size on model storm intensity

It is expected that a TC is much weaker in the analyses (ERA-40) than in the best track because winds in the former are area-averaged while those in the latter are point estimates. The weak intensity of storms in the analyses is evident in the plots in Fig.2. The graphical representation of intensity is quantified in Table 3 and presented as a bar plot in Fig.7. Consider first the columns for D1 in the table (which is the data plotted in Fig. 2). Of the 417 cases of 6-h positions of TC, there are 160 JTWC typhoons but no TC was measured in ERA-40 that has a wind speed greater than 33 ms-1. The same is observed for D2 and D3. There are too many tropical depressions and tropical storms in ERA-40 indicating the much weaker winds in the dataset.

	D1			D2			D3		
	JTWC	ERA-40	Model	JTWC	ERA-40	Model	JTWC	ERA-40	Model
Depression	156	296	248	156	290	138	129	237	94
Tropical storm	101	121	160	97	117	241	73	53	190
Typhoon	160	0	9	154	0	28	88	0	6
No. of cases	417	417	417	407	407	407	290	290	290

Table 3. Counts of 6-h TC intensity from JTWC best track, ERA-40 and model output for the domain experiments.

To assess whether the regional model is able to better simulate the winds and hence the intensity of TC, the frequency of the 6-h model TC is compared with JTWC and ERA-40 for the three domains. The regional model is able to generate more tropical storms and typhoons: 28 of the observed 154 typhoons from JTWC (18%) were detected in D2 and 6 of the 88 (7%) in D3. The increase in intensity is least in the large domain D1 with 9 typhoons of 160 (6%) observed. This indicates that the physically-based downscaling of the regional model has improved the wind simulation over the domain. The size and placement of domain boundaries influence not only the simulation of the tracks but also feedback on a more realistic simulation of the winds in a TC. While D1 gave a better performance in terms of smaller zonal and meridional errors, D2 gave a better simulation of TC intensity.

CONCLUSIONS

This study shows the potential of regional climate models to detect tropical cyclones and simulate their tracks on a seasonal scale (JJAS) in the Philippine region. The value added to the simulation is attributed to the increased resolution and model physics and is shown to be a function of domain size and placement of boundaries. A very small domain simulates the tracks reasonably well but the seemingly good simulation may be due to artificially constrained errors due to the boundary. For all domains, model tracks were found to be displaced northwards, fast in the westward migration and are generally slow to intensify. Basing on the zonal and meridional errors, D1 is considered the optimal domain configuration in this study. The size and placement of D1 allow the capture of the most number of TC affecting the Philippine region, avoid the constraints of boundaries and minimize propagation of errors. In terms of wind simulation, the model was able to generate typhoons which are absent in the forcing data, indicating the skill of the downscaling. More typhoons were formed in D2 than in D1. These results indicate that the size and placement of domain boundaries influence not only the simulation of the tracks but also the simulation of the winds in a TC.

The regional model in this study is run at a resolution of 45 km and is forced at the boundaries by ERA-40 data which is globally observed data at a resolution of about 250 km. The use of reanalyses data allows evaluation of model results given "perfect" boundary conditions. If GCM integrations are used as boundary forcing for the regional model and if the quality of GCM outputs approach that of reanalyses, tracks and intensities of cyclones can be forecast on a seasonal scale. This study is a pioneering initiative on investigating the feasibility of making seasonal forecast

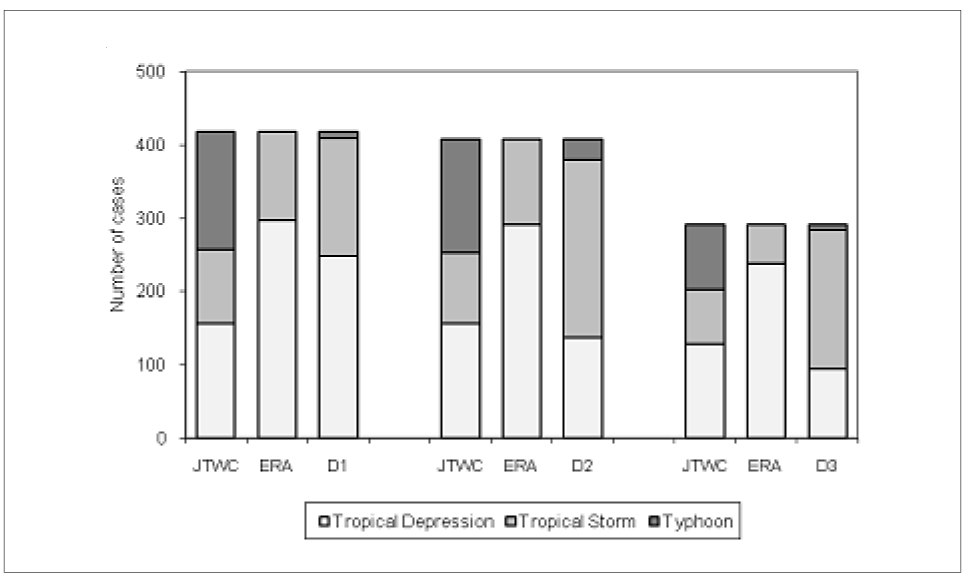


Fig 7. Frequency of 6-h model tropical cyclone intensity for the three domains relative to JTWC and ERA-40.

of TC from regional models in the Philippine region. Follow-up studies must be done to build on the methodology developed for this study. These include further improvement of the tracking algorithm particularly in tracking interacting storms, sensitivity studies on the influence of the land surface / terrain on storms, and the influence of the simulated TC structure and intensity on the choice of convective parameterizations.

ACKNOWLEDGEMENTS

This study was funded by the Office of the Vice Chancellor for Research and Development (OVCRD), UP Diliman as Project No. 040402. The authors are grateful for the technical support extended by the International Centre for Theoretical Physics on the use of RegCM3 and for providing all data sets required by the model.

REFERENCES

Bengtsson, L, et al. 1995. Hurricane-type vortices in a general circulation model. *Tellus, 47A.* 175-196.

Camargo and Zebiak. 2002. Improving the detection and tracking of tropical cyclones in atmospheric general circulation models. *Wea and Forecasting.* 17, 1152-1162.

_______ and Sobel. 2004. Formation of tropical storms in an atmospheric general circulation model. *Tellus. 56A,* 56-67.

Chan, J, J. Shi and K Liu. 2001. Improvements in the seasonal forecasting of tropical cyclone activity over the western North Pacific. *Wea and Forecasting.* 16, 491-498.

Chouinard, C., J.Mailhot, H.L. Mitchell, A. Staniforth and T. Hogue. 1994. The Canadian regional data assimilation system: operational and research applications. *Mon Wea Rev,* 122,1306-1325.

De Elia R. and R. Laprise. 2002. Forecasting skill limits of nested, limited-area models: A perfect model approach. Mon Wea Rev. 130, 2006-2023.

Elsberry, R (ed). et al. 1987. A Global View of Tropical Cyclones. 185 pp.

Giorgi F, et al. 1993a. Development of a second generationregional climate model (RegCM2). Part I. boundary layer and radiative transfer processes. *Mon Wea Rev,* 121, 2794-2813.

______ et al. 1993b. Part II. Convective processes and assimilation of lateral boundary conditions. *Mon Wea Rev* 121, 2814-2832.

Kallberg, P., P. Berrisford, B. Hoskins, A. Simmons, S. Uppala, S. Lamie-Thepaut and R. Hine. 2005. ECMWF Re-Analysis Project Report Series: 19. *Era-40 Atlas.* Reading, England, 191 pp.

Landman, W. , A. Seth and S. Camargo. 2005. The effect of regional climate model domain choice on the simulation of tropical cyclone-like vortices in the southwestern Indian Ocean. *J Climate,* 18, 1263-1274.

Nguyen and K. Walsh. 2001. Inter-annual, decadal and transient greenhouse simulation of tropical cyclone-like vortices in a regional climate model of the South Pacific. *J Climate,* 14, 3043-3054.

Seth, A. and F. Giorgi. 1998. The effects of domain choice on summer precipitation and sensitivity in a regional climate model. *J Climate,* 11, 2698-2712.

Vitart, F. 1997. Simulation of interannual variability of tropical storm frequency in an ensemble of GCM integrations. *J Climate.* 10, 745-760.

_______, D. Anderson and T. Stockdale. 2003. Seasonal forecating of tropical cyclone landfall over Mozambique. *J Climate,* 16, 3932-3945.

Walsh, K. and I. Watterson. 1997. Tropical cyclone-like vortices in a limited area model: comparison with observed climatology. *J Climate,* 10:2240-2259.