

# Tropical cyclones over the North Indian Ocean: experiments with the high-resolution global icosahedral grid point model GME

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**Abstract** In this paper, an attempt has been made to conduct a numerical experiment with the high-resolution global model GME to predict the tropical storms in the North Indian Ocean during the year 2007. Numerical integrations using the icosahedral hexagonal grid point global model GME were performed to study the evolution of tropical cyclones, viz., Akash, Gonu, Yemyin and Sidr over North Indian Ocean during 2007. It has been seen that the GME model forecast underestimates cyclone's intensity, but the model can capture the evolution of cyclone's intensity especially its weakening during landfall, which is primarily due to the cutoff of the water vapor supply in the boundary layer as cyclones approach the coastal region. A series of numerical simulation of tropical cyclones have been performed with GME to examine model capability in prediction of intensity and track of the cyclones. The model performance is evaluated by calculating the root mean square errors as cyclone track errors.

## 1 Introduction

North Indian Ocean (NIO), which includes regions of Bay of Bengal and the Arabian Sea, account for 7–8% of the tropical cyclones (out of around 80) over the globe per year. In general, the tropical cyclones which form in NIO region are less intense than those formed over the North-western Pacific or North Atlantic Oceans. Sporadically, very severe tropical cyclones develop in the Bay of Bengal. The Regional Specialized Meteorological Center (RSMC) of India Meteorological Department (IMD) has given the classification of the low-pressure systems (IMD 2008). In NIO, low-pressure systems with surface wind speeds less than 17 knots are low-pressure areas, 17–27 knots are depression and 28–33 knots are considered as deep depressions. The low-pressure systems with two or more closed isobars in which the surface wind speeds in cyclonic circulation as 34–47 knots with a large-scale pressure deficit at the center are classified as Cyclones. When the wind speeds are 48–63 knots, it is Severe Cyclonic Storm and 64–119 knots are very Severe Cyclonic Storm and when it exceeds 120 knots it is known as Super Cyclones. In June 2007, there was an intense tropical storm over the Arabian Sea. It was the first recorded tropical cyclone of the intensity of Category 4 of Saffir–Simpson Hurricane scale (<http://www.nhc.noaa.gov/>) in the Arabian Sea. The cyclones over the Bay of Bengal and the Arabian Sea cause lot of damages to property and loss of life pertaining to high density of population around these basins. Primarily the cyclone causes tidal bores and surges, which inundate coastal areas causing considerable loss of life and damage to property. Strong winds also cause a lot of damage.

During the year 2007, twelve low-pressure systems formed over the North Indian Ocean area (Mazumdar et al. 2008). These include one Super Cyclone (Gonu) of the

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intensity of the Category 4 Hurricane, one very Severe Cyclonic Storm (Sidr), two Cyclonic Storms (Yemyin and Akash), five deep depressions and three depressions. In this study, we have attempted to simulate only those systems which reached at least the category of tropical cyclone, viz., Akash, Yemyin, Gonu and Sidr using high-resolution global model GME. The Cyclonic Storm ‘Akash’ formed during the Pre-monsoon season (March–May), Super Cyclonic Storm ‘Gonu’ and Cyclonic Storm ‘Yemyin’ during the Southwest Monsoon Season (June–September) and the Very Severe Cyclonic Storm ‘Sidr’ during the Post-monsoon Season (October–December). Though, none of these Cyclonic Storms had their landfall over the Indian region, study of these tropical cyclones is of immense importance for the coastal areas. The Super Cyclone ‘Gonu’ was the first ever Category 4 Hurricane formed over the Arabian Sea. Gonu caused massive devastation, including loss of life and damage to property and the infrastructure, particularly in the Sharqiyah region and the governorate of Muscat. There were reports about damage caused to power lines, water supplies, roads, flyovers as well as loss of human life. Widespread rainfall activity occurred due to ‘Akash’ in Nagaland–Manipur–Mizoram–Tripura on 15 May 2007 and over Assam and Meghalaya on 15 and 16 May 2007. There was no damage in India due to ‘Yemyin’ Cyclonic Storm. Widespread rainfall activity with heavy to very heavy falls occurred in Andaman and Nicobar Islands from 10 to 12 November, 2007 and in Assam and Meghalaya and Nagaland–Manipur–Mizoram–Tripura on 16 November 2007 due to ‘Sidr’.

In general, regional or mesoscale models are used to simulate tropical storms (e.g. Patra et al. 2000; Xie et al. 2008; Gopalkrishnan et al. 2008; Deshpande et al. 2010; Srinivas et al. 2013; Thomas et al. 2014). The studies of tropical cyclones with the global models are very limited (Manganello et al. 2012; Zarzycki and Jablonowski 2015). The GME model employed in this study is a latest generation icosahedral hexagonal grid point model and it is used operationally in Germany. Authors have already used the same model with same resolution for the simulations of heavy precipitation event occurred in Mumbai in India on 26 July 2005 (Kumkar et al. 2011). The model was able to simulate this extreme rainfall event reasonably well. Therefore, we have used GME for the simulation of tropical cyclones and to investigate whether GME model is capable of capturing mesoscale phenomena.

In this study, an attempt has been made to conduct numerical experiments with numerical weather prediction model (high-resolution global model) GME to simulate four tropical storms over the NIO during the year 2007. Moreover, icosahedral hexagonal grid point approach of model is a new kind of approach for the weather and cyclone prediction.

## 2 Methodology

### 2.1 GME model

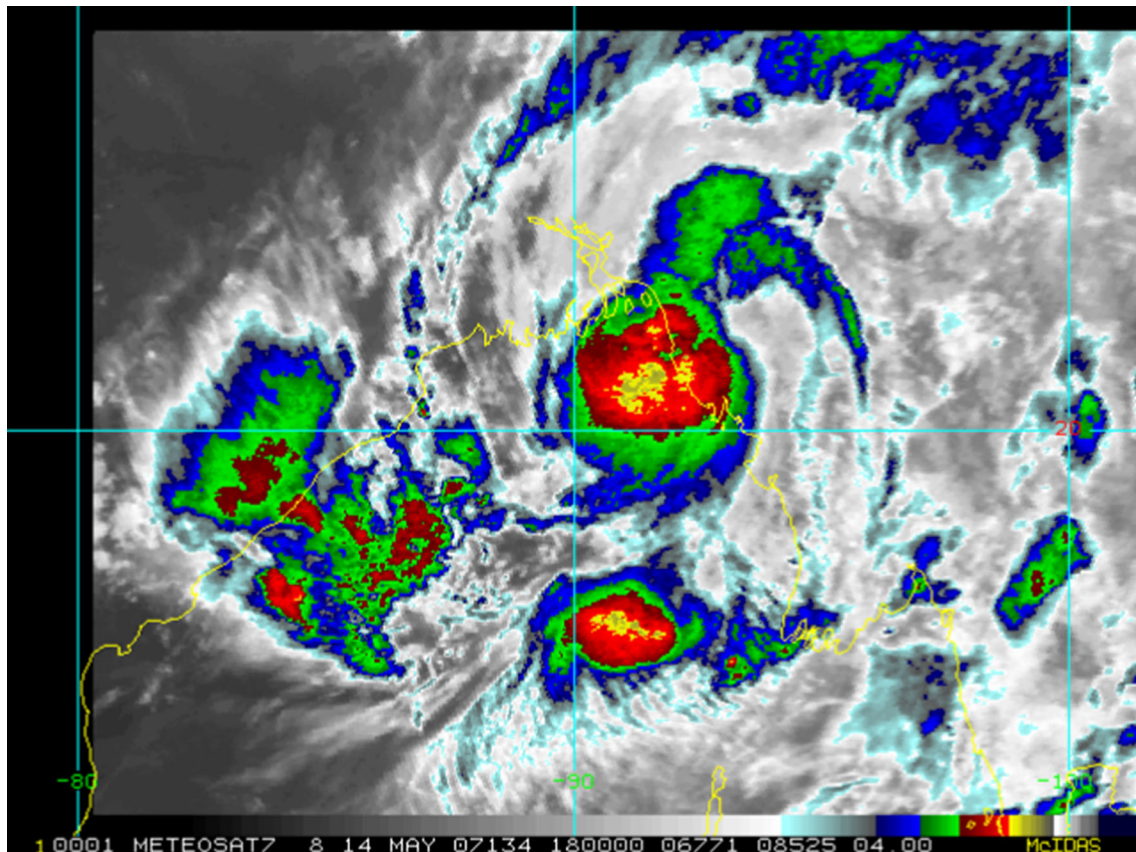
The GME is an operational Numerical Weather Prediction global model developed by the German Weather Service (Majewski et al. 2002). GME makes use of grid point approach with quasi-uniform icosahedral–hexagonal grid. In model, prognostic equations for wind components, temperature, and surface pressure are solved by the semi-implicit Eulerian method. Only the two prognostic moisture equations (specific water vapor content and specific cloud liquid water content) employs semi-Lagrangian advection in the horizontal direction to ensure monotonicity and positive definiteness. GME constructs geodesic grid by starting with ordinary icosahedrons inscribed inside a unit sphere. The icosahedron consists of 12 vertices. As a first step in the construction of a spherical geodesic grid, each face of the icosahedrons is subdivided into four new faces by bisecting the edges. This recursive bisecting method is repeated until a grid of the desired resolution is obtained. Such grids are called as quasi-homogeneous in the sense that the area of the largest cell is only a few percent greater than the area of the smallest cell.

The model used in this study has horizontal resolution of 40 km with 40 vertical levels. It has 368,642 total number of grid points per layer. By combining the areas of pairs of the original adjacent icosahedral triangles, the global grid can logically also be viewed as comprising ten rhombuses or diamonds, each of which has  $n_1 \times n_1$  unique grid points, where  $n_1$  is the number of equal intervals into which each side of the original icosahedral triangles is divided. For 40 km horizontal resolution of GME,  $n_1$  is equal to 192. To ease in the implementation of the model on parallel computer diamond-wise domain decomposition is carried out. For the 2-D domain decomposition the  $(n_1 + 1)^2$  grid points of each diamond are distributed to  $n_1 \times n_2$  processors. Thus, each processor computes the forecast for a sub-domain of each of the ten diamonds. This is a simple effective strategy to attain a good load balancing between processors. Details of model description are available in Majewski et al. (2002).

A major advantage of the icosahedral–hexagonal grid is the avoidance of the so-called pole problem that exists in conventional latitude–longitude grids. The singularities at the poles lead to a variety of numerical difficulties including a severe limitation on the time step size unless special measures are undertaken. These difficulties simply vanish for grids not having such singularities (e.g. Majewski et al. 2002; Ringler et al. 2000). GME uses Hybrid vertical coordinate system (Simmons and Burridge 1981) and is handled by a set of dedicated parameterization

**Table 1** Model physics and dynamical features of the global model-GME

|                                                                    |                                                                                                                     |
|--------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------|
| Dynamical features of GME model                                    |                                                                                                                     |
| Horizontal grids                                                   | Icosahedral hexagonal, 40 km, Arakawa A grid, all variables on triangle                                             |
| Vertical grids                                                     | Hybrid coordinate system (sigma-pressure) Simmons and Burridge 1981                                                 |
| Vertical layers                                                    | 40                                                                                                                  |
| Top layer pressure                                                 | 10 hPa                                                                                                              |
| Time integration schemes                                           | Eulerian, split semi-implicit treatment of surface pressure, temperature, horizontal wind components, gravity waves |
|                                                                    | Semi-Lagrangian, positive-definite, monotone advection of water substances                                          |
| Time step                                                          | 133.33 s                                                                                                            |
| Initial condition                                                  | ECMWF IFS T511 with 91 levels                                                                                       |
| Number of active soil layers                                       | 7                                                                                                                   |
| Model physics of GME (Physical parameterizations)                  |                                                                                                                     |
| Radiation and clouds                                               | Ritter and Geleyn (1992)                                                                                            |
| Grid scale precipitation                                           | Doms and Schättler (2003)                                                                                           |
| Deep and shallow Convection                                        | Tiedtke (1989)                                                                                                      |
| Turbulent fluxes in atmospheric boundary layer and free atmosphere | Müller (1981; Louis 1979; Mellor and Yamada 1974)                                                                   |
| Soil model                                                         | Heise and Schrödin (2002)                                                                                           |
| Subgrid-scale orography                                            | Lott and Miller (1997)                                                                                              |
| Sea-ice model                                                      | Mironov and Ritter (2003; 2004)                                                                                     |

**Fig. 1** Meteosat-7 enhanced IR imagery (4 km Mercator) of cyclone Akash at 18 UTC 14 May 2007



modules. The physical parameterizations and dynamical features of the GME model are given in Table 1. Initialization schemes of GME are designed to remove noise from the forecast while introducing acceptably small changes to the analysis and forecasts. GME model has shown remarkable improvements in seasonal prediction over tropics (Chaudhari and Oh 2004) and for exploring exceptionally heavy rainfall phenomenon over Mumbai (Kumkar et al. 2011). GME model was implemented on CRAY X1E and IBM p695 supercomputers. To ease the data visualization, selected forecast fields are interpolated horizontally from the icosahedral–hexagonal grid to regular latitude–longitude one. In addition, some multilevel fields are interpolated vertically from 40 model layers to selected pressure levels.

## 2.2 Synoptic description of the tropical cyclone cases

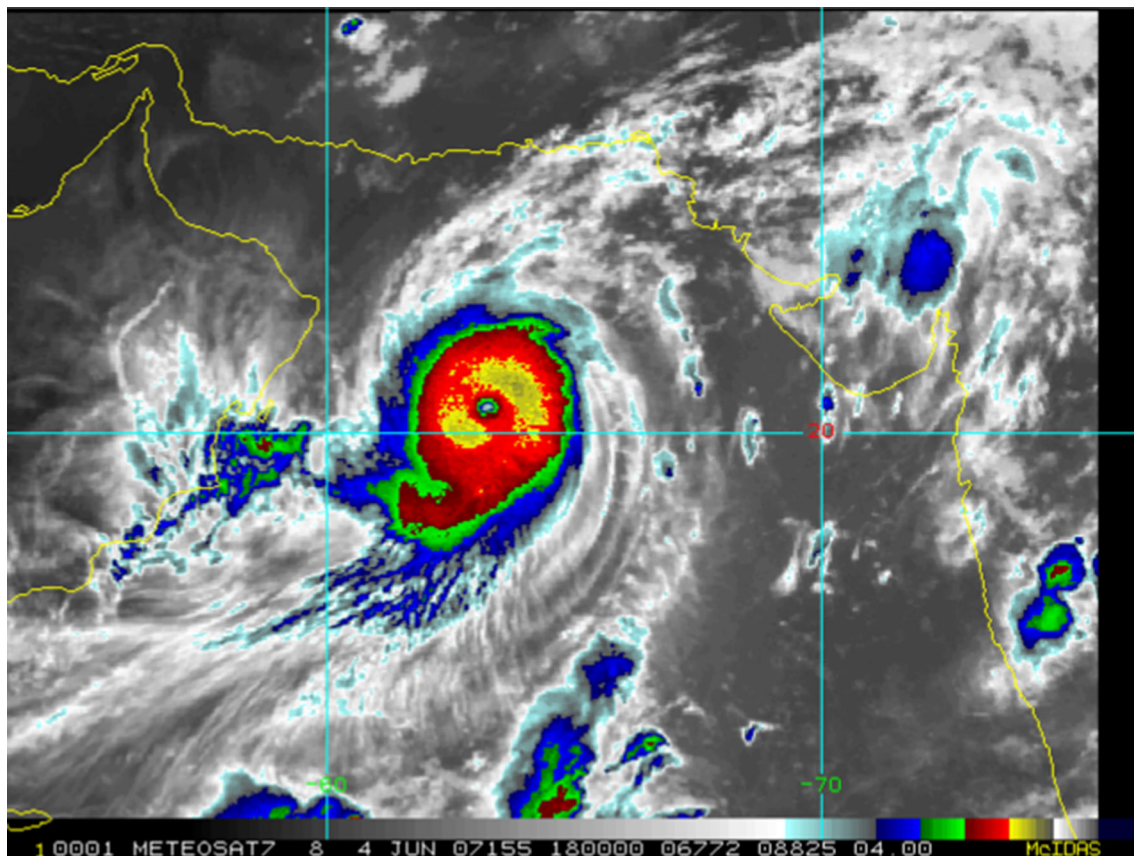
### 2.2.1 Akash

This system developed as a depression in the Bay of Bengal on 10 UTC 12 May 2007 near west–southwest of Yangon, Myanmar. It was still a depression until 03 UTC 13 May and

started moving northwards with speed of 7 knots. At 21 UTC on 13 May, it became a deep depression with 1 min average winds of 30 knots. By 03 UTC on 14 May, the system intensified into the Cyclonic Storm near latitude 16.5°N, longitude 91.0°E with the maximum sustained wind speed of 50 knots. The Cyclonic Storm Akash reached its peak intensity of 65 knots at 18 UTC 14 May (started moving south southeast of Chittagong and inland into extreme southeastern Bangladesh with minimum centre pressure of 988 hPa). The satellite-enhanced infrared image at the peak is presented in Fig. 1. At 03 UTC 15 May, the system was located at latitude 21.2°N, longitude 92.2°E with the maximum sustained winds of 45 knots. After reaching its peak intensity, the system made landfall about 115 km south of Chittagong and weakened rapidly as it moved inland.

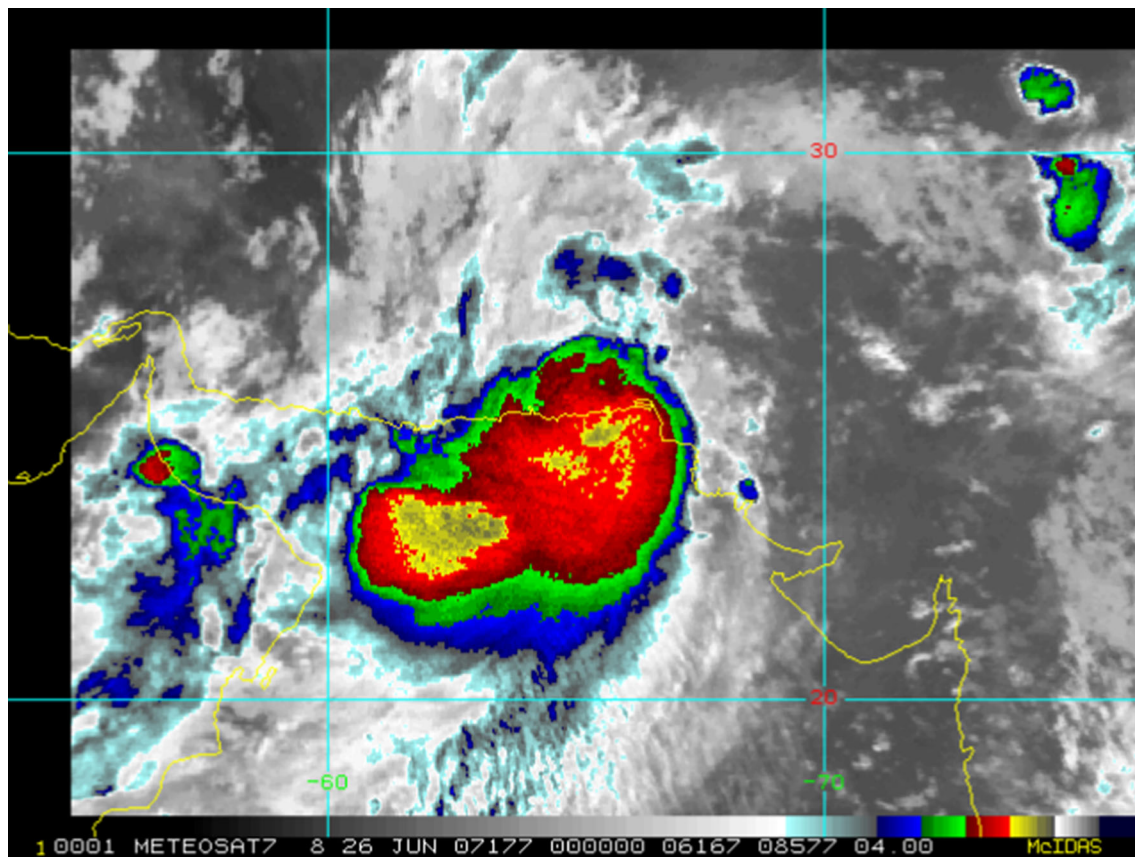
### 2.2.2 Gonu

This system evolves as a depression over the East central Arabian sea at 18 UTC 1 June 2007 with center near latitude 15°N, longitude 68°E. By 09 UTC 2 June, it moved westwards and intensified into Cyclonic Storm with 10 min maximum sustained winds of 50 knots and remained in this state for 15 h. On 00 UTC 3 June, it intensified further into



**Fig. 2** Meteosat-7 enhanced IR imagery (4 km Mercator) of cyclone Gonu at 18 UTC 4 June 2007





**Fig. 3** Meteosat-7 enhanced IR imagery (4 km Mercator) of cyclone Yemyin at 00 UTC 26 June 2007

a severe Cyclonic Storm (centered at latitude 15.5°N, longitude 66.5°E) with central pressure of 988 hPa and remained in this state for next 18 h. It further intensified into a very severe Cyclonic Storm by 18 UTC 3 June with central pressure of 980 hPa centered at latitude 18°N, longitude 66°E and remained in this state for the next 21 h. The system moved west–northwestward on 15 UTC 4 June and further intensified into a Super Cyclonic Storm centered at latitude 20°N, longitude 64°E with minimum central pressure of 920 hPa and maximum sustained winds of 120 knots. The satellite-enhanced infrared image at the peak is presented in Fig. 2. It could not sustain its peak strength for very long as it stayed in this state only for next 6 h. Then it further moved into northwestward and weakened to a very severe Cyclonic Storm with central pressure of 935 hPa centered at latitude 20.5°N, longitude 63.5°E on 21 UTC 4 June and remained in this state for next 48 h. On 21 UTC 6 June, it weakened and made its landfall on the coast of Oman.

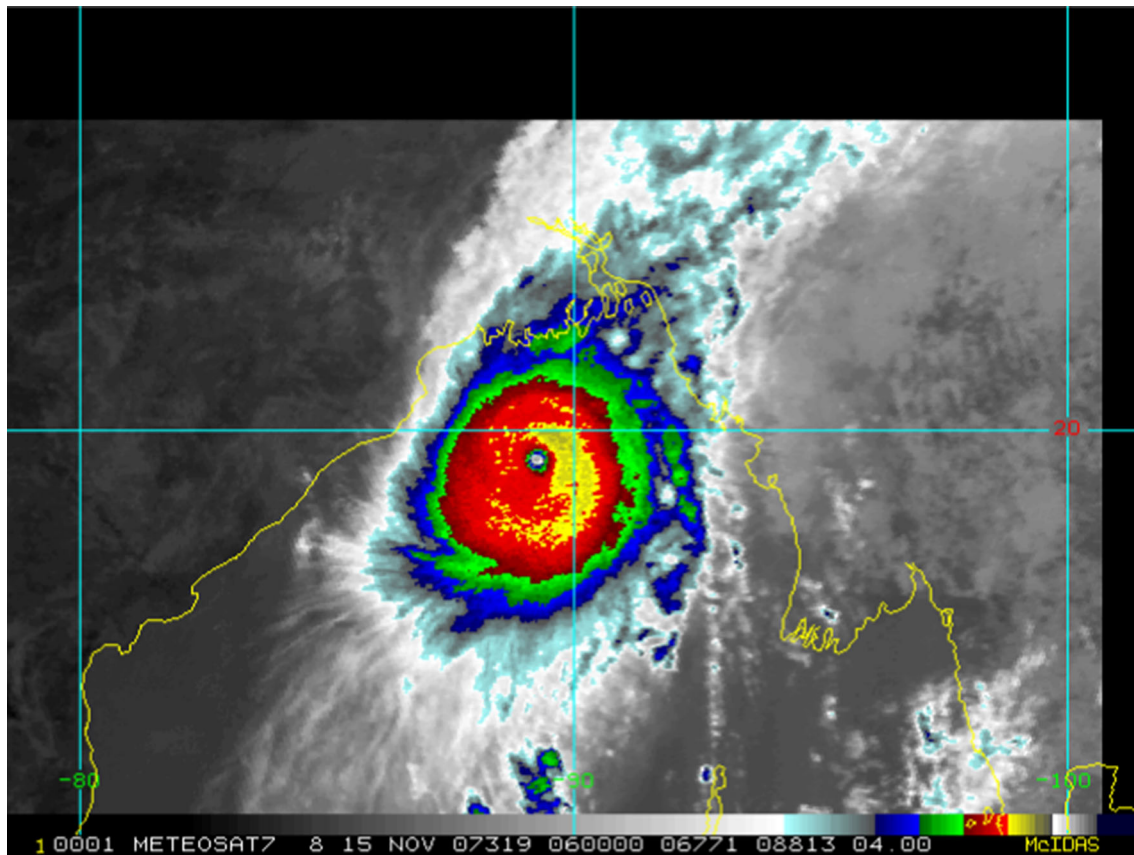
### 2.2.3 Yemyin

This system initially originated on 21 June 2007 in the afternoon near the Bay of Bengal as a tropical depression.

The system moved west northwest towards northern Andhra Pradesh coast. It weakened and made first landfall near Kakinda early on 22 June due to land interaction and wind shear. By 24 June, the system revived due to strong monsoonal low-level flow which contributed to increased cyclonic vorticity with low vertical wind shear and warm sea surface temperatures (SST). It entered the north Arabian Sea and redeveloped as a depression on 25 June 2007 at 06 UTC with centre around latitude 22.9°N, longitude 67.3°E with center pressure of 990 hPa and winds of 26 knots. On the same day, the system intensified into a deep depression and was located at 90 km within city of Karachi. The system moved northwest and finally made its second landfall along the Makran coast of Balochistan on early morning of 26 June 2007 at 03 UTC resulting in torrential rains and weakened thereafter. The satellite-enhanced infrared image at the peak is shown in Fig. 3.

### 2.2.4 Sidr

The system was identified as tropical low-pressure system on 11 November 2007 near southeast Bay of Bengal and Andaman Sea. It became a depression at 09 UTC 11 November at latitude 10°N, longitude 92°E. At 18 UTC, it



**Fig. 4** Meteosat-7 enhanced IR imagery (4 km Mercator) of cyclone Sidr at 06 UTC 15 November 2007

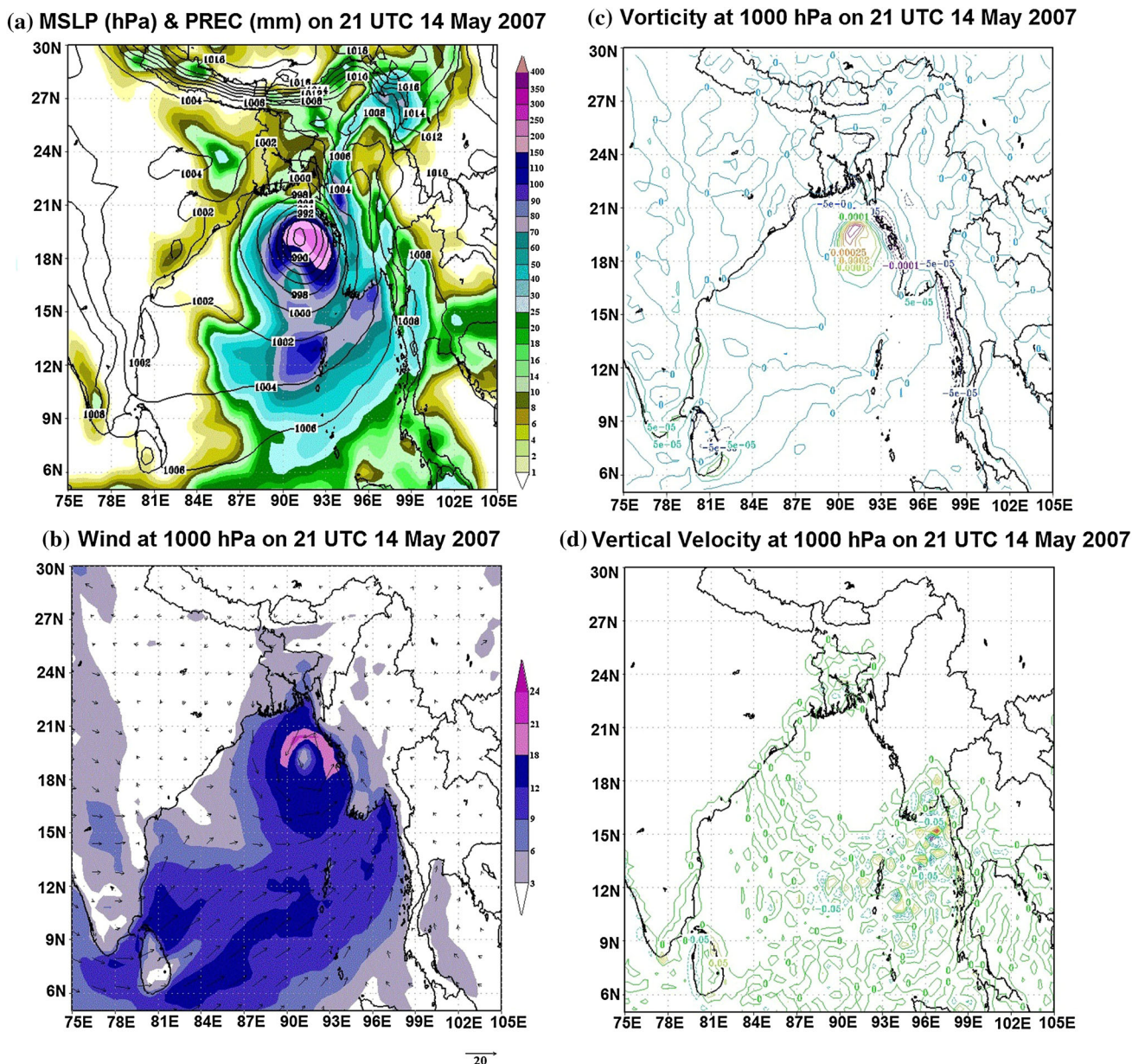
**Table 2** Root mean square (RMS) errors ( $^{\circ}$ ) and maximum winds (m/s) of the tropical cyclones simulated by GME model

| Cyclone cases | Initial conditions (00 UTC, 2007) | RMS error ( $^{\circ}$ ) | Maximum winds (m/s) |
|---------------|-----------------------------------|--------------------------|---------------------|
| Akash         | 12 May                            | 2.14                     | 17.15               |
|               | 13 May                            | 1.50                     | 24.04               |
| Gonu          | 30 May                            | 5.79                     | 19.82               |
|               | 31 May                            | 4.80                     | 20.00               |
|               | 1 June                            | 4.18                     | 15.10               |
| Yemyin        | 2 June                            | 2.91                     | 15.51               |
|               | 20 June                           | 4.73                     | 21.40               |
|               | 21 June                           | 7.32                     | 21.85               |
|               | 22 June                           | 5.26                     | 26.25               |
| Sidr          | 23 June                           | 2.11                     | 31.86               |
|               | 9 Nov                             | 6.65                     | 19.57               |
|               | 10 Nov                            | 3.21                     | 22.97               |
|               | 11 Nov                            | 5.12                     | 19.17               |

tuned into a deep depression near latitude  $10.5^{\circ}\text{N}$ , longitude  $91.5^{\circ}\text{E}$ . The system further moved westward at latitude  $10.5^{\circ}\text{N}$ , longitude  $91.0^{\circ}\text{E}$  at 03 UTC on 12 November and became a Cyclonic Storm. It further moved north-westwards and developed as a severe Cyclonic Storm with minimum central pressure of 968 hPa near latitude  $11.5^{\circ}\text{N}$ , longitude  $90.0^{\circ}\text{E}$  at 12 UTC 12 November. Later it became

a very severe Cyclonic Storm at 03 UTC 13 November. It further intensified and reached minimum central pressure of 944 hPa on 15 November at 12 UTC near region of  $21^{\circ}\text{N}$ ,  $89^{\circ}\text{E}$  and started moving north-northeastwards. It maintained the same intensity of 90 knots from 12 November to 15 November. The satellite-enhanced infrared image at the peak is shown in Fig. 4. The system





**Fig. 5** **a** Simulated mean sea level pressure (PMSL) and accumulated precipitation (24 h) at the time of actual landfall of cyclonic Storm Akash, **b** Simulated wind pattern at 1000 hPa. **c** Vertical component

of vorticity at 1000 hPa. **d** Vertical velocity at 1000 hPa. All at 21UTC 14 May (time of actual landfall) with the initial condition of 00UTC, 13 May, 2007

further intensified with sustained wind speed of 115 knots and crossed the west Bangladesh coast. After landfall at 17 UTC 15 November, the system weakened into Cyclonic Storm and then became a depression and remained till 16 November.

### 2.3 Numerical experiments and data used

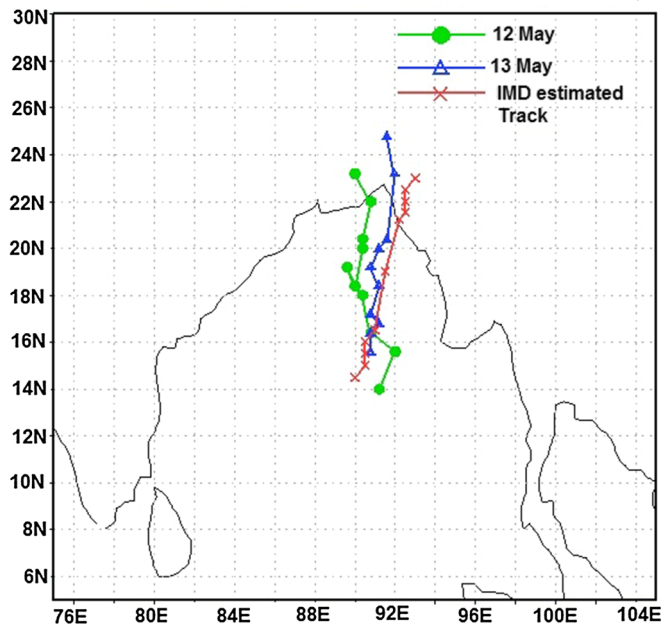
The initial state for the model run was based on operational analysis dataset of European Centre for Medium-Range Weather Forecasts (ECMWF). ECMWF dataset has

resolution of T511 and it has 91 vertical levels. The initial state is prepared with the data assimilation scheme which consists of the (a) multivariate optimal interpolation scheme to analyze surface pressure, temperature, humidity and horizontal wind components (b) snow analysis scheme (c) analysis of sea surface temperature performed once at a day and (d) analysis of sea-ice fraction performed once a day. The GME model initialization is done with the Digital Filtering Initialization (DFI; Lynch 1997) to remove the high-frequency initial noise from the forecast. DFI involves a 3-h adiabatic backward integration and a



**Fig. 6** Regional Specialized Meteorological Centre (RSMC), India Meteorological Department (IMD) estimated best track and GME simulated cyclone tracks of Cyclonic Storm Akash

### Cyclone Tracks for Akash - Initial dates 12, 13 May 2007



3-h diabatic forward one centered on the initial time. The Cyclonic Storm ‘Akash’ has been simulated with different initial conditions of 12 and 13 May, 2007. The Super Cyclonic Storm ‘Gonu’ has been simulated with initial conditions of 30, 31 May, 1 and 2 June 2007. The Cyclonic Storm ‘Yemyin’ is simulated with initial conditions of 20, 21, 22, and 23 June 2007. Very Severe Cyclonic Storm ‘Sidr’ is simulated with initial conditions of 9, 10, and 11 November 2007. In all the cases, the model run is carried out for 240 h.

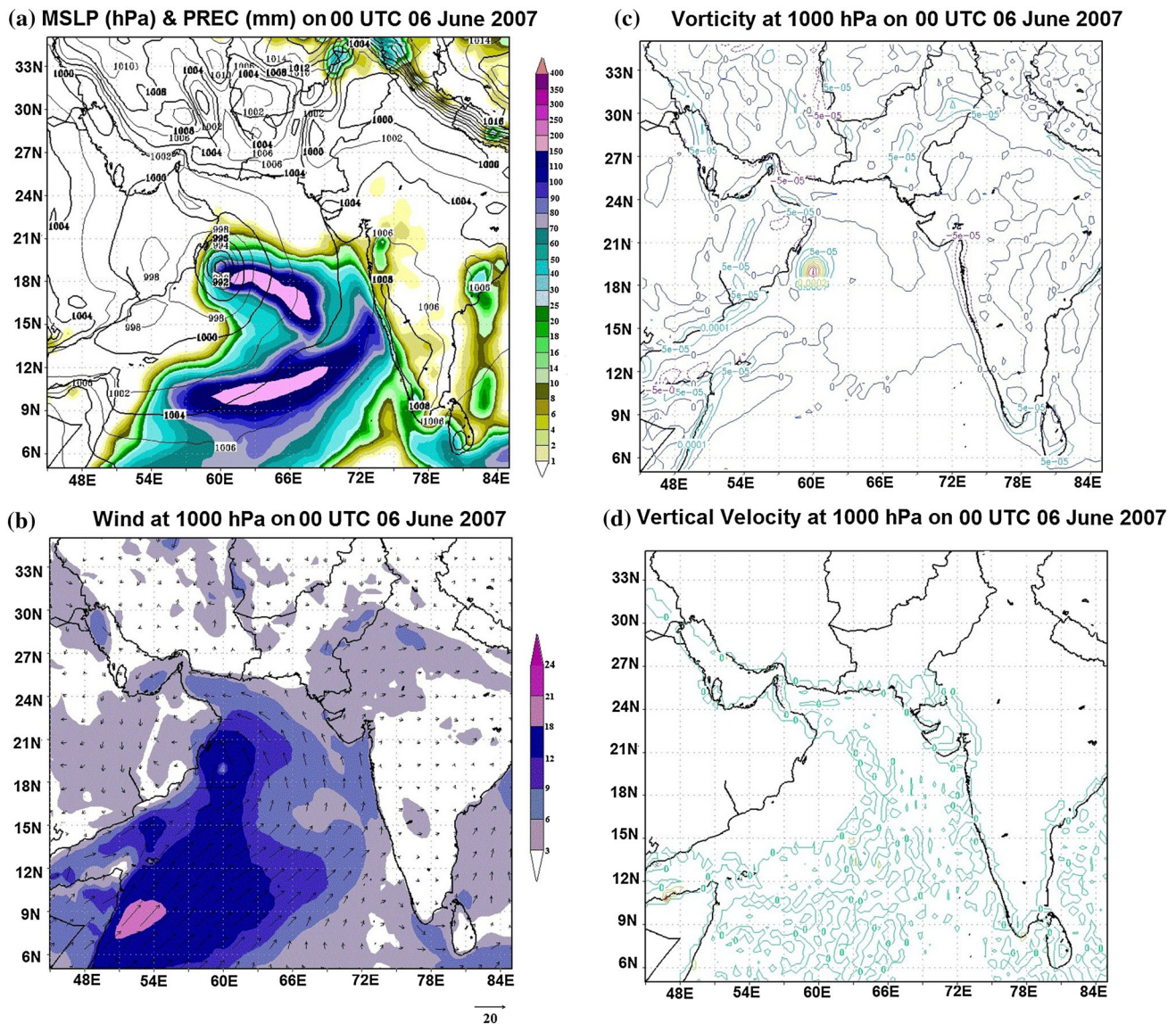
#### 2.4 Analysis methods

Every year the Regional Specialized Meteorological Center for tropical cyclones over NIO of IMD (India Meteorological Department, RSMC: <http://www.rsmcnewdelhi.imd.gov.in>) publishes the detailed analyses of tropical cyclones occurred in the North Indian Ocean region. As per IMD, cyclone eye is a region of mostly calm weather at the center of the cyclone with roughly circular area of 30–65 km in diameter and can be as much as 15% lower barometric pressure than that of outside of the cyclone. It is surrounded by the eyewall, where the most severe weather occurs. Most often the cyclone eye is visible in the satellite imageries. We have calculated the track errors as root mean square (RMS) errors between observed (IMD estimated best track data) and the model-predicted one. The track errors for all cyclone case with all initial conditions are

calculated and presented in Table 2. Moreover, mean maximum winds for each initial condition for all cyclone cases are calculated and presented in Table 2 and explained in the conclusion section.

### 3 Tropical cyclone climatology of North Indian Ocean (NIO)

In the North Indian Ocean, tropical cyclones form mainly during the pre-monsoon and the post-monsoon seasons (Asnani 2006; Webster et al. 2005). During the Southwest Monsoon period four to five low-pressure systems develop over the NIO, but very rarely do they intensify into tropical cyclone stage. During the cold weather season hardly does any low-pressure system form in this region. The number of tropical storms over the Bay of Bengal is much greater than that of the Arabian Sea. The maximum number of storms in the Bay of Bengal occurs in the months of October and November. In the Arabian Sea the largest number of storms is observed in May, June, October and November (Das 2005; Chinthalu et al. 2002). Most of the storms in the Bay of Bengal have their genesis to the north of 16°N. Mostly the storms over the Bay of Bengal have their landfall over Andhra Pradesh, Orissa and West Bengal. Sometimes they move northeastward and cross Bangladesh coast. The Arabian Sea storms normally affect the coast of Maharashtra, Goa and Gujarat.



**Fig. 7** a Simulated mean sea level pressure (PMSL) and accumulated precipitation (24 h) at the time of actual landfall of Super Cyclonic Storm Gonu. b Simulated wind pattern at 1000 hPa. c Vertical

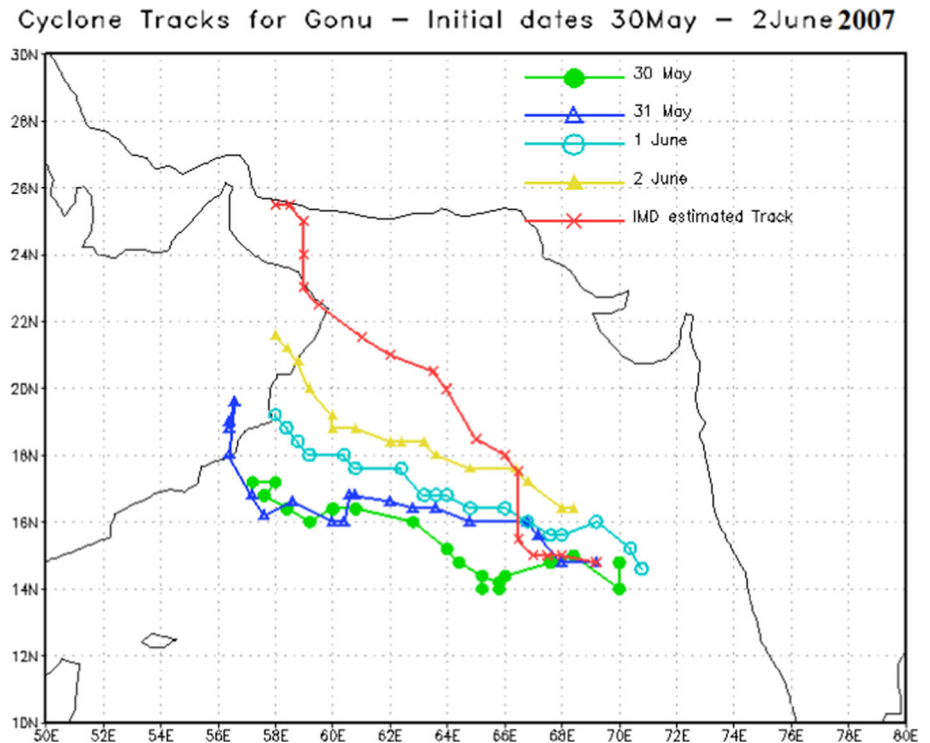
component of vorticity at 1000 hPa. d Vertical velocity at 1000 hPa. All at 00UTC 6 June with the initial condition of 00UTC, 2 June, 2007

#### 4 Results and discussion

The model used in this study has horizontal resolution of 40 km, 40 vertical levels and time step of 133 s. The model-predicted intensity in terms of MSLP (mean sea level pressure) and maximum wind are validated with observation (Mazumdar et al. 2008). Model-predicted track positions are validated with Regional Specialized Meteorological Centre-IMD-based best track dataset. The results are briefly presented in the manuscript. After finding the estimated position of central pressure, cyclone tracks have

been drawn. The root mean square errors have been calculated for each case with different initial conditions. The model was integrated for 240 h starting from 00 UTC for all the initial conditions in all experiments. The simulation of Cyclonic Storm 'Akash' has been done with the initial conditions of 12 and 13 May, 2007. The central pressures, wind patterns, vertical component of vorticity and vertical velocity have been presented in Fig. 5a–d. The cyclone tracks are shown in Fig. 6 for Akash. For Akash, the RMS error is 1.5° of latitude for the initial condition of 13 May 2007. The lowest estimated central pressure (ECP) was

**Fig. 8** RSMC IMD estimated and GME simulated cyclone tracks of Super Cyclonic Storm Gonu



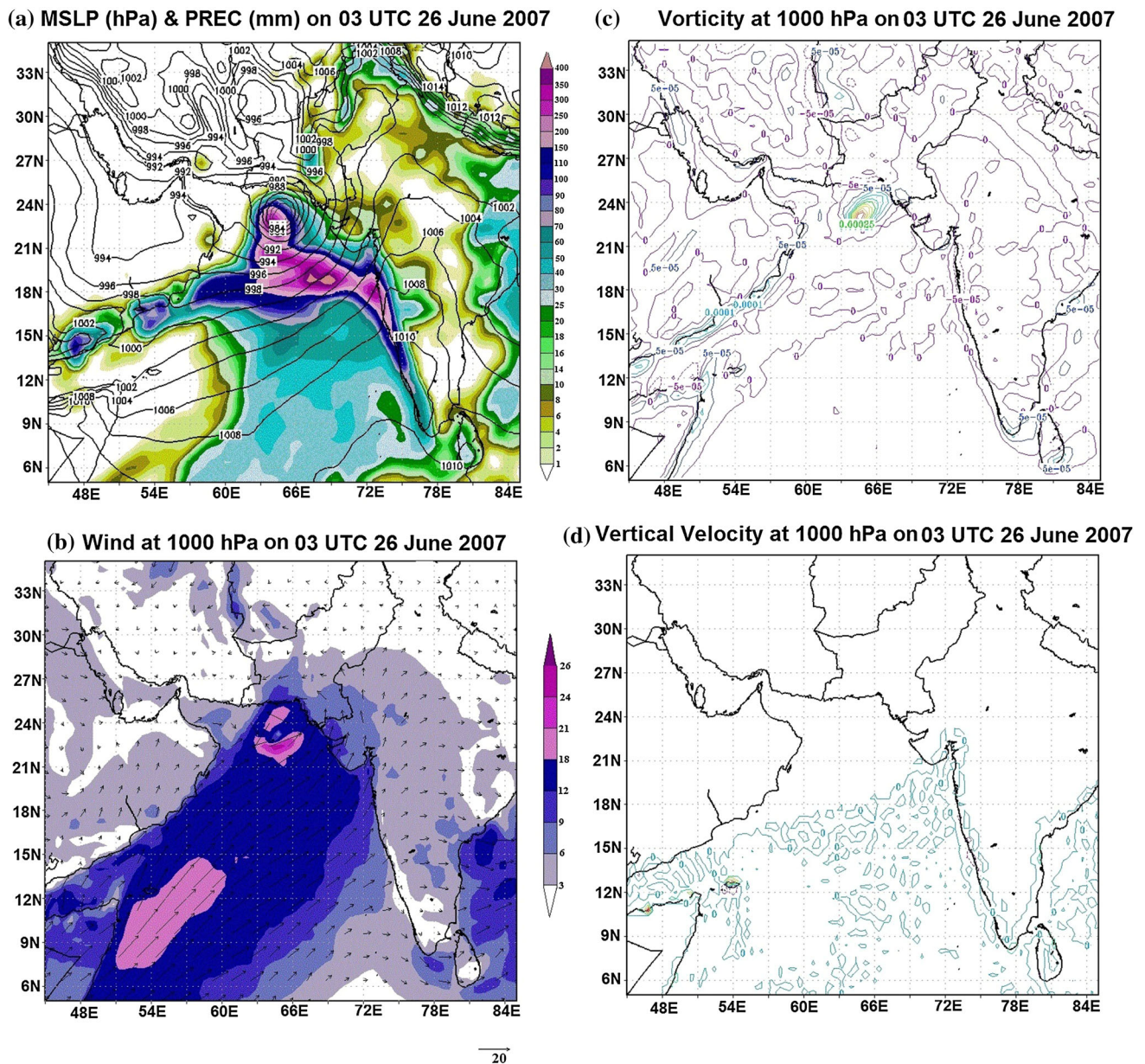
988 hPa and maximum estimated surface wind (MESW) speed was 45 kt ( $23 \text{ ms}^{-1}$ ) (Mazumdar et al. 2008). The model depicts lowest central pressure about 987 hPa at the time of landfall and the rainfall of 100–130 mm with the initial conditions of 13 May 2007. Therefore, it can be concluded that the model has been able to simulate the cyclone Akash reasonably well (since GME is a global model). Model exhibits maximum wind speed of 17.15 and  $24.04 \text{ ms}^{-1}$  with the initial conditions of 12 and 13 May, respectively. The model gives the vertical component of maximum vorticity of  $3.5 \times 10^{-4}$  and  $5.9 \times 10^{-4} \text{ s}^{-1}$  with the initial conditions of 12, and 13 May 2007, respectively, at 1000 hPa level. Model shows maximum positive vertical velocity as 0.66 Pa/s at the time of landfall.

The simulation of Super Cyclonic Storm ‘Gonu’ has been done with the initial conditions of 30, 31 May, 1 and 2 June 2007. The central pressures, wind patterns, vertical component of vorticity and vertical velocity have been presented in Fig. 7a–d. The Cyclone tracks are drawn and are shown in Fig. 8 for Gonu. The RMS errors have been calculated with each initial condition. For Gonu, the RMS error comes out to be  $5.7^\circ$ ,  $4.8^\circ$ ,  $4.1^\circ$  and  $2.9^\circ$  latitudes for the initial conditions of 30 May, 31 May, 1 and 2 June 2007, respectively. The lowest ECP was 920 hPa and MESW speed of 127 kt ( $65 \text{ ms}^{-1}$ ) based on Mazumdar et al. (2008). The model

shows lowest Central pressure about 979 hPa at the time of first landfall and 969 hPa at the time of second landfall and the rainfall of 150–200 mm. Model also shows maximum wind speed of 19.82, 20, 15.10,  $15.51 \text{ ms}^{-1}$  with the initial conditions of 30 May, 31 May, 1 June and 2 June, respectively. Although the model has shown the location of central pressure reasonably well, it has underestimated values of central pressure and wind speeds. For Gonu, model gives the vertical component of maximum vorticity of  $2.9 \times 10^{-4}$ ,  $3.4 \times 10^{-4}$ ,  $1.1 \times 10^{-4}$ ,  $9.6 \times 10^{-4} \text{ s}^{-1}$  with the initial conditions of 30 May, 31 May, 1 June and 2 June 2007, respectively, at 1000 hPa level. Model depicts maximum positive vertical velocity as 0.45 Pa/s at the time of landfall.

The simulation of Cyclonic Storm ‘Yemyin’ has been done with the initial conditions of 20, 21, 22, and 23 June, 2007. The central pressures, wind patterns, vertical component of vorticity and vertical velocity are shown in Fig. 9a–d. The cyclone tracks of observation and model are given in Fig. 10 for Yemyin. The RMS errors with the initial conditions of 20, 21, 22, and 23 June 2007 are  $4.7^\circ$ ,  $7.3^\circ$ ,  $5.2^\circ$  and  $2.1^\circ$  latitude, respectively. The lowest ECP was 986 hPa and MESW speed was 35 kt ( $18 \text{ ms}^{-1}$ ) based on IMD (Mazumdar et al. 2008). The model shows lowest central pressure about 978 hPa at the time of landfall and the rainfall of 350–400 mm with the initial conditions of 23 June 2007. Model shows maximum wind speed of 21.4,





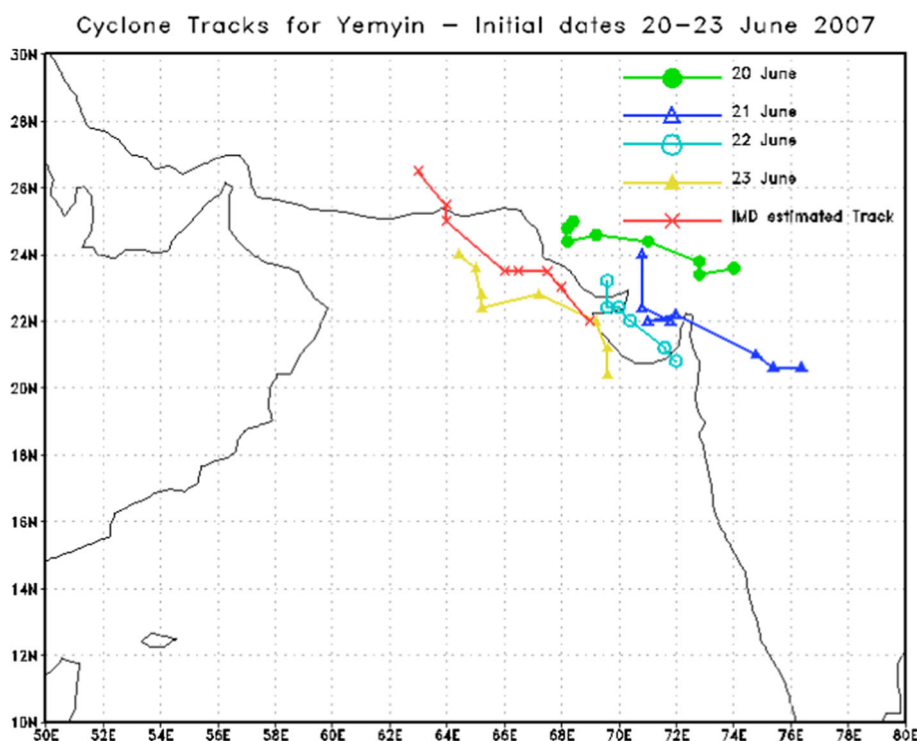
**Fig. 9** a Mean sea level pressure (PMSL) and accumulated precipitation (24 h) at the time of actual landfall of Cyclonic Storm Yemyin. b Simulated wind pattern at 1000 hPa. c Vertical component of

vorticity at 1000 hPa. d Vertical velocity at 1000 hPa. All at 03UTC 26 June with the initial condition of 00UTC, 23 June, 2007

21.85, 26.25, 31.86  $\text{ms}^{-1}$  with the initial conditions of 20, 21, 22, and 23 June, 2007, respectively. It can be concluded that model has overestimated the central pressure and the wind speeds. For Yemyin, model gives the vertical component of maximum vorticity of  $2 \times 10^{-4}$ ,  $4.6 \times 10^{-4}$ ,  $5.1 \times 10^{-4}$ ,  $9.9 \times 10^{-4} \text{ s}^{-1}$  with the initial conditions of 20, 21, 22, and 23 June 2007, respectively, at 1000 hPa level. Model shows maximum positive vertical velocity as 0.55 Pa/s at the time of landfall.

The simulation of Very Severe Cyclonic Storm ‘Sidr’ has been done with the initial conditions of 9, 10, and 11 November 2007. The central pressures, wind patterns, vertical component of vorticity and Vertical Velocity have been presented in Fig. 11a–d. The cyclone tracks are illustrated in Fig. 12 for Sidr. The RMS errors have been computed for each initial condition. For Sidr, the RMS errors are 6.6°, 3.2° and 5.1° latitude for the initial condition of 9, 10 and 11 November 2007. The lowest ECP

**Fig. 10** RSMC IMD estimated and GME simulated cyclone tracks of Cyclonic Storm Yemyin



was 944 hPa and MESW speed was 108 kt ( $56 \text{ ms}^{-1}$ ) (Mazumdar et al. 2008). The model shows lowest central pressure of about 990 hPa and the rainfall of 350–400 mm with the initial conditions of 10 November 2007. Model shows maximum wind speed of 19.57, 22.97 and  $19.17 \text{ ms}^{-1}$  with the initial conditions of 9, 10 and 11 November, 2007, respectively. Model depicts maximum positive vertical velocity as  $0.74 \text{ Pa/s}$  at the time of landfall. It can, therefore, be concluded that the model has underestimated both the central pressure and the wind speed. For Sidr, the model gives the vertical component of maximum vorticity of  $5.1 \times 10^{-4}$ ,  $4.8 \times 10^{-4}$  and  $3.1 \times 10^{-4} \text{ s}^{-1}$  with the initial conditions of 9, 10 and 11 November, 2007, respectively, at 1000 hPa level.

IMD estimated center pressure and GME model-predicted central pressure are presented in Table 3. Thomas et al. (2014) calculated the mean track errors for the tropical cyclone Sidr as 260.22 km ( $2.3^\circ$ ) with the RAMS (Regional Atmospheric Modeling System) model. Rakesh and Goswami (2011) have also calculated the mean track errors for the Gonu and Sidr systems with the mesoscale model WRF with three different data assimilation options, viz., no assimilation, GBES (global background global error statistics) and RBES (regional background global error statistics). For Gonu, for the first day errors were 150, 193 and 120 km (i.e.  $1.3^\circ$ ,  $1.8^\circ$ ,  $1.1^\circ$ ) with no assimilation, GBES and RBES, respectively. For day 2 and 3, the errors

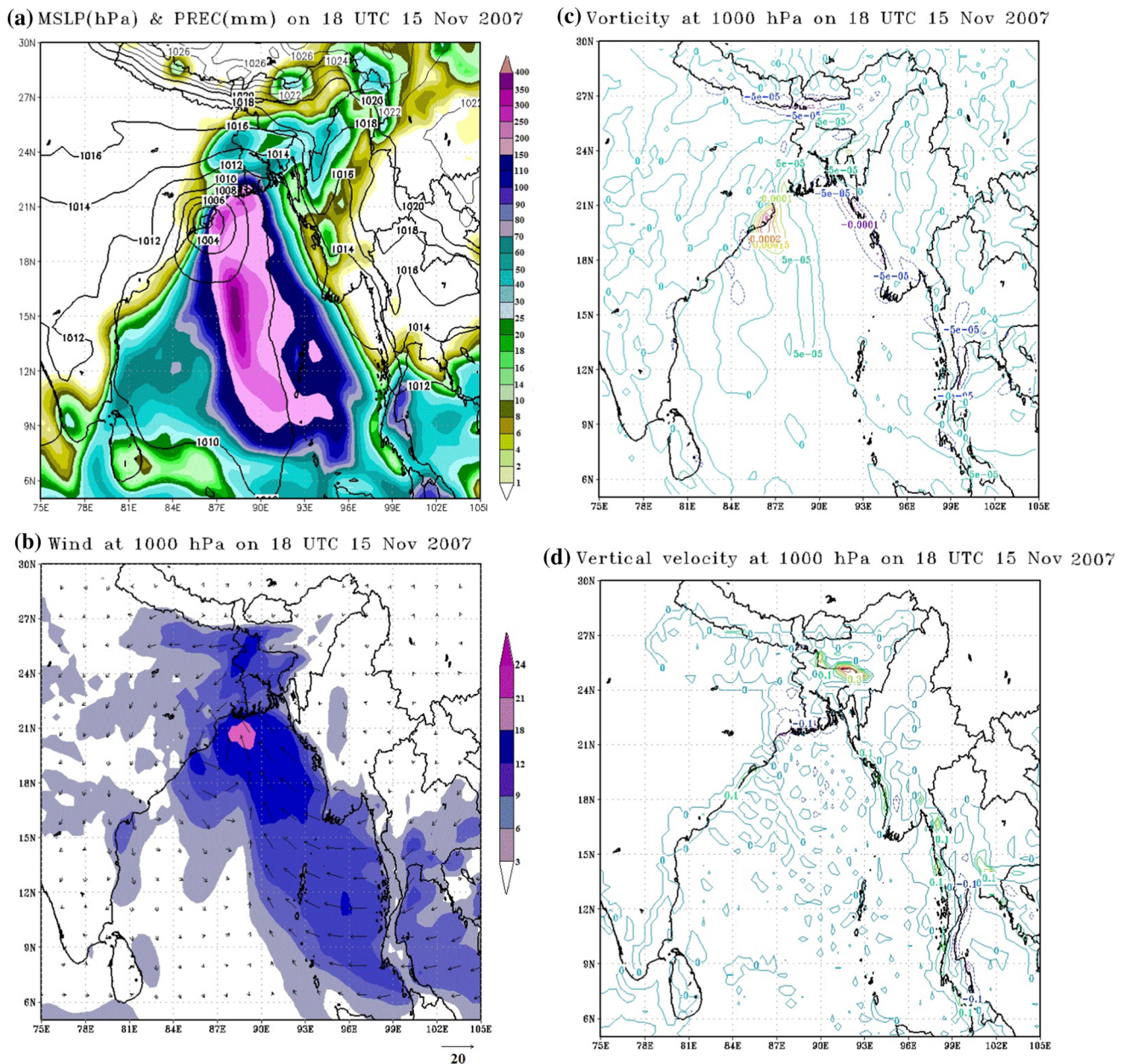
increased to double. For Sidr, for first day errors were 144, 168 and 112 km ( $1.2^\circ$ ,  $1.6^\circ$ ,  $1.0^\circ$ ) with no assimilation, GBES and RBES, respectively. For day 2 and 3, the errors are more than that of the first day. There are no studies of the tropical cyclones in NIO with the global models and for these particular cases. Compared with these regional model studies for the tropical cyclones Gonu and Sidr, the global model GME performs well in terms of the cyclone track errors.

## 5 Summary and conclusions

In this study, numerical experiments with global model GME are carried out for the simulation of four tropical storms over the NIO during the year 2007. Model has implemented the new approach of icosahedral hexagonal grid point for cyclone simulations. This geodesic grid point approach is free from so-called pole problem that exists in conventional latitude–longitude grids. It means that these models are equally good for studies at high latitudes also. Initialization schemes of GME and use of high-resolution ECMWF datasets have also helped in better simulation of GME numerical experiments.

The model-predicted intensity in terms of MSLP and maximum wind speeds are validated with observation. Model-predicted track positions are validated with





**Fig. 11** **a** Mean sea level pressure (PMSL) and accumulated precipitation (24 h) at the time of actual landfall of very severe cyclonic Sidr. **b** Simulated wind pattern at 1000 hPa. **c** Vertical

component of vorticity at 1000 hPa. **d** Vertical velocity at 1000 hPa. All at 18UTC 15 November with the initial condition of 00UTC, 10 November, 2007

Regional Specialized Meteorological Centre-IMD-based best track dataset. The results are in considerable agreement with observation. Additionally, track errors as root mean square (RMS) errors between observed (IMD estimated best track data) and the model predicted are calculated. The model has been able to simulate the Cyclonic Storm 'Akash' reasonably well. However, model simulation indicates underestimation of the central pressure and the wind speed in the case of Super Cyclonic Storm Gonu. In the case of the cyclone Yemyin, it has overestimated these meteorological

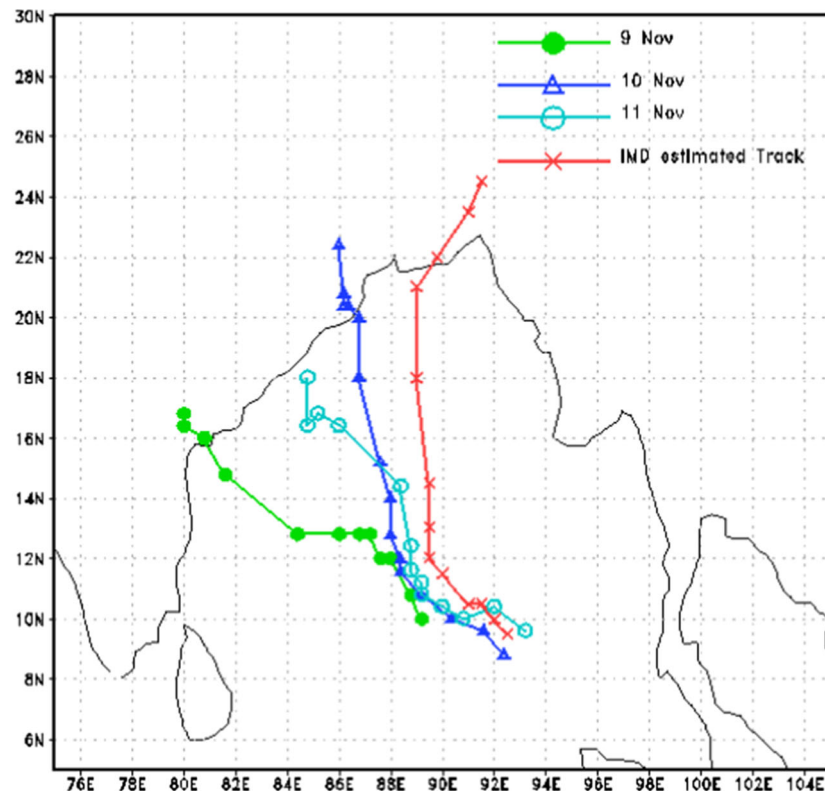
parameters. In the case of Sidr, the model has been able to capture the observed track of the cyclone considerably well. The model is also able to reproduce the accumulated rainfall and it is in reasonable agreement with observation.

GME model has a tendency to underestimate the central pressure and winds for a very intense system over the Bay of Bengal. However, the model is capable of simulation of a tropical storm of moderate intensity. GME is a global model and not a regional or mesoscale model. In spite of being a global model, GME has considerable skill



**Fig. 12** RSMC IMD estimated and GME simulated cyclone tracks of very Severe Cyclonic Storm Sidr

**Cyclone Tracks for Sidr— Initial dates 9 – 11 November 2007**



**Table 3** Lowest central pressure of the tropical cyclones: estimation from IMD and prediction from GME model

| Tropical cyclone case with initial condition | IMD estimated center pressure (hPa) | Predicted center pressure (hPa) by GME |
|----------------------------------------------|-------------------------------------|----------------------------------------|
| Akash                                        | 988                                 | 987                                    |
| Gonu                                         | 920                                 | 969                                    |
| Yemyin                                       | 986                                 | 978                                    |
| Sidr                                         | 944                                 | 990                                    |

to capture the tropical storms over the North Indian Ocean.

Icosahedral models can utilize maximum processing elements (i.e. processors) on high-performance computing system. So that operational task can be completed within short duration of time. It will provide additional benefit for the operational usage of GME model.

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## References

- Asnani GC (2006) Tropical Meteorology 2:9–125
- Chaudhari HS, Oh JH (2004) Climate simulation with global icosahedral-hexagonal gridpoint model GME, Second Conference on Climate Change, Taegu, Korea, pp 129–133
- Chinthalu GR, Seetaramayya P, Ravichandran M, Mahajan PN (2002) The Bay of Bengal and tropical cyclones. *Curr Sci* 82:4
- Das PK (2005) The monsoons. National Book Trust, India, pp p220–p222
- Deshpande S, Pattanaik S, Salvekar PS (2010) Impact of physical parameterization schemes on numerical simulation of super cyclone Gonu. *Nat Hazards* 55:211–231
- Doms G, Schättler U (2003) The nonhydrostatic limited-area model LM (Lokal-Modell) of DWD. Part I: Scientific Documentation. Deutscher Wetterdienst (DWD), Offenbach, March 2003
- Gopalkrishnan SG, Rogers RF, Atlas R, Marks FD and Aberson S (2008) Advanced numerical prediction and modeling of tropical cyclones using WRF-NMM modeling system. 28th Conference on Hurricanes and Tropical Meteorology, Miami, Florida
- Heise E, Schrodin R (2002) Aspects of snow and soil modelling in the operational short range weather prediction models of the German Weather Service. *Journal of Computational Technologies*, Vol. 7, Special Issue. In: Proceedings of the International Conference on Modelling, Databases and Information Systems for Atmospheric Science (MODAS), Irkutsk, Russia, June 25–29, 2001, pp 121–140

- IMD (2008) Forecasters' guide—Forecasting circular No. 1/1998, pp. 1–141. <http://www.imdpune.gov.in/Weather/reports.html>. Accessed 29 Nov 2016
- Kumkar YV, Sen PN, Chaudhari HS, Oh JH (2011) Simulation of heavy rainfall over Mumbai on 26 July 2005 using high resolution Icosahedral Gridpoint model GME. *Int J Meteorol* 35:4–13
- Lott F, Miller M (1997) A new sub-grid scale orographic drag parameterization: its formulation and testing. *Quart J Roy Meteor Soc* 123:101–128
- Louis JF (1979) A parametric model of vertical eddy fluxes in the atmosphere. *Boundary-Layer Meteorol* 17:187–202
- Lynch P (1997) The Dolph-Chebyshev window: a simple optimal filter. *Mon Wea Rev* 125:655–660
- Majewski D, Liermann D, Prohl P, Ritter B, Buchhold M, Hanisch T, Paul G, Wergen W, Baumgardner J (2002) The operational global icosahedral–hexagonal gridpoint model GME: description and high-resolution tests. *Mon Weather Rev* 130:319–338
- Manganello JV, Hodges KI, Kinter JL, Cash BA, Marx L, Jung T, Achuthavariar D, Adams JM, Althuler EL, Huang B, Ek Jin, Stan C, Towers P, Wedi N (2012) Tropical cyclone climatology in a 10-km global atmospheric GCM: toward weather-resolving climate modeling. *J Clim* 25:3867–3893
- Mazumdar AB, Khole M, Devi SS (2008) Cyclones and depressions over North Indian Ocean during 2007. *Mausam* 59(3):273–290
- Mellor GL, Yamada T (1974) A hierarchy of turbulence closure models for planetary boundary layers. *J Atmos Sci* 31:1791–1806
- Mironov D, Ritter B (2003) A first version of the ice model for the global NWP system GME of the German Weather Service. WGNE Blue Book
- Mironov D, Ritter B (2004) A new sea ice model for GME. Technical note. Deutscher Wetterdienst, Offenbach am Main, p 12
- Müller E (1981) Turbulent flux parameterization in a regional-scale model. ECMWF Workshop on planetary boundary layer parameterization, pp 193–220
- Patra PK, Santhanam MS, Potty KVJ, Tewari M, Rao PLS (2000) *Curr Sci* 79:70–78
- Rakesh V, Goswami P (2011) Impact of background error statistics on forecasting of tropical cyclones over the north Indian Ocean. *J Geophys Res* 116:D20130. doi:10.1029/2011JD015751
- Ringler TD, Heikes RP, Randall DA (2000) Modeling the atmospheric general circulation using a spherical geodesic grid: a new class of dynamical cores. *Mon Weather Rev* 128:2471–2490
- Ritter B, Geleyn JF (1992) A comprehensive radiation scheme for numerical weather prediction models with potential applications in climate simulations. *Mon Wea Rev* 120:303–325
- Simmons AJ, Burridge DM (1981) An energy and angular-momentum conserving finite-difference scheme and hybrid vertical coordinates. *Mon Weather Rev* 109:758–766
- Srinivas CV, Bhaskar Rao DV, Yesubabu V, Baskaran R, Venkatraman B (2013) Tropical cyclone predictions over the Bay of Bengal using the high-resolution advanced research weather research and forecasting (ARW) model. *Q.J.R. Meteorol Soc* 139:1810–1825. doi:10.1002/qj.2064
- Thomas A, Samala BA, Kaginalkar A (2014) Simulation of north Indian Ocean tropical cyclones using RAMS numerical weather prediction model. *Trop cyclone res rev* 3:44–52. doi:10.6057/2014TCRR01.04
- Tiedtke M (1989) A comprehensive mass flux scheme for cumulus parameterization in large-scale models. *Mon Wea Rev* 117:1779–1800
- Webster PJ, Holland GJ, Curry JA, Chang HR (2005) Changes in Tropical cyclone number, duration and intensity in a warming environment. *Science* 309:1844–1846
- Xie L, Liu B, Zhang X, Peng S, Liu H (2008) Numerical simulation of tropical cyclone intensity using an air-sea-wave coupled prediction system, 28th Conference on Hurricanes and Tropical Meteorology, Miami, Florida
- Zarzycki CM, Jablonowski C (2015) Experimental tropical cyclone forecasts using a variable-resolution global model. *Mon Wea Rev* 143:4012–4037