Track prediction of very severe cyclone 'Nargis' using high resolution weather research forecasting (WRF) model

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The recent very severe cyclonic storm (VSCS) 'Nargis' over the Bay of Bengal caused widespread destruction over Myanmar after hitting the coast on 2 May 2008. The real time forecasting of the VSCS 'Nargis' was a very difficult task as it did not follow the normal westerly/northwesterly track. In the present study, a detailed diagnostic analysis of the system 'Nargis' is carried out initially to investigate the features associated with this unusual movement and subsequently the real time forecast of VSCS 'Nargis' using high resolution advanced version weather research forecasting (WRF) model is presented. The advanced research WRF model was run for 72 h at 27 km and 20 km resolutions with 28, 29, 30 April and 1 May as the initial conditions. The diagnostic study indicates that the recurvature of the system 'Nargis' was mainly associated with:

- upper level southerly/southwesterly steering wind at 200 hPa level associated with anticyclonic circulation over southeastern sector of the centre of the system,
- higher SST (29°C or more) with higher positive anomalies over the region to the northeast of the cyclone centre, and
- large negative 24 h pressure changes and large vorticity maximum to the east of the system.

The real time track forecast using the WRF model run at 27 km and 20 km resolution based on the initial conditions of 28 April (when the system was only 550 km away from the Indian coast) indicated that the system had a northeasterly forecast track and was not expected to cross the Indian coast. Similarly, based on 29 April initial condition the system showed east/east-northeasterly movement towards the Myanmar coast. The east/east-northeasterly movement of the 'Nargis' was persisting in the forecast based on 30 April and 1 May initial conditions with respective landfall errors of 85 km and 50 km with 27 km resolution, which reduces to 30 km and 40 km respectively with 20 km resolution, however, with a landfall time delay of about 10 h. Improvement of mean forecast errors at different forecast hours is noticed in WRF model run at higher resolution compared to that run at lower resolution. Thus, it is very clear that the advanced version WRF model had captured movement of the system reasonably well almost 3 days in advance. Consistence with the diagnostic analysis the WRF model forecast also indicates southerly/southwesterly strong steering wind at 200 hPa level and maximum pressure fall to the east of the system.

1. Introduction

Tropical cyclones (TCs) are one of the most dangerous natural calamities throughout the globe. Every year, they cause considerable loss of life and do immense damage to property. India and Bangladesh have a coastline of more than 8000 km,

which is prone to very severe cyclone formations in the Arabian Sea and Bay of Bengal. These occur during the pre-monsoon (April–May), early monsoon (June), late and post-monsoon (September–November) periods. Originating in both the Bay of Bengal and Arabian Sea, tropical cyclones often attain velocities of more than 160 km/h and

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are notorious for causing intense rain and storm tides (surges) as they cross the coast of India, Bangladesh and other coasts. Strong winds, heavy and torrential rains and the cumulative effect of storm surges and astronomical tides are the three major elements of tropical cyclone disaster. This is also the basin where TCs do the most damage due to the combined effects of terrain, geography, and lack of communications. The need for sea surface temperature (SST) greater than 26.5°C and a deep lower level moist layer and absence of strong vertical shear for development from a tropical low to a cyclonic storm and further intensification has been referred to in many studies (Gray 1992; Frank 1977). More than 200,000 people perished in the Bhola cyclone of 1970 in Bangladesh.

The cyclonic disturbances in the north Indian Ocean move predominantly along westerly/northwesterly direction. However, some cyclonic disturbances recurve from an initial northwesterly direction to a northerly direction (often after reaching $15\text{--}20^{\circ}\text{N}$ latitude) and finally towards northeasterly direction (IMD 1996). The detailed review of the synoptic and thermodynamic characteristics to predict the movement and intensification/decay of the cyclonic storm has been discussed by Krishna Rao (1997). A review of the dynamic characteristics of the movement and intensification is given by Mohanty and Gupta (1997). The motion of TC is the result of a complex interaction between a number of internal and external influences. Environmental steering is typically the most prominent external influence on a tropical cyclone, accounting for as much as 70–90% of the motion. Theoretical studies have shown that in the absence of environmental steering, tropical cyclones move poleward and westward due to the internal influences (Chan and Gray 1982; Elsberry *et al* 1987). The dominant influence on movement is the large-scale environmental steering. These tracks of movement are mainly due to the normal upper airflow pattern prevailing in the cyclone period. However, many forces act on the cyclonic disturbance and consequently its motion is never along a smooth path. There is also non-linear interaction between the cyclonic disturbance and the basic current in which it is embedded. Hence, the movement of the storm depends on many factors including synoptic, thermodynamic and dynamical factors. Analysis by Srinivasan and Ramamurthy (1973) found that the position of the ridge line at 200 hPa is seen to govern the movement to a large extent. They have seen that when the centre is north of the ridge line but within 3° of it, in the majority of the cases a dominant easterly component of motion appears, whereas when the storm reaches beyond 3° north of the ridge line, it gets a definite eastward motion. The recent very severe cyclonic storm (VSCS)

of Bay of Bengal ‘Nargis’ also recurved from its north and northwesterly movement and became easterly and caused widespread destruction over Myanmar after the landfall on 2 May 2008. But it did not follow the climatological cyclone track, which leads to India or Bangladesh. Thus, it is very important to monitor the system throughout its lifespan and provide accurate track forecasts to minimize the colossal damages/losses.

Predictions of tropical cyclones have improved steadily over the last three decades, mostly due to a combination of better observations, especially the satellite and radar, improvement in dynamical models and improved understanding of physical processes and mechanisms that govern the motion of tropical cyclones. The current emphasis of international tropical cyclone research is to achieve greater accuracy of tropical cyclone track and intensity prediction, especially in the short range (48–72 h in advance), by maximizing the use of non-conventional data, meso-scale analysis, and the physical parameterization in non-hydrostatic environment at higher model resolution. In India, development of objective techniques for forecasting track of TCs began in 1972 (Sikka and Suryanarayana 1972) by using a computer oriented half persistence and half climatology technique. Singh and Saha (1978) used case studies for forecasting movement of TCs by adopting a primitive equation barotropic model. In recent years, Mohanty and Gupta (1997), and Gupta and Bansal (1997) have used multi-level primitive equation models with parameterization of physical processes. Quasi-Lagrangian Model (QLM) has also been implemented in IMD for operational track forecast up to 72 h in the year 2000. Prasad and Rama Rao (2003) have evaluated the QLM and its performance is found to be even better. In the present study, the high resolution Advanced Research WRF (ARW) meso-scale model adopted from NCAR is run at 27 km and 20 km resolution to get the real time forecast of the system ‘Nargis’ to investigate the capability of the model to forecast such a difficult track of the system. Initially, a detailed analysis of dynamical and thermodynamical features associated with the recurvature and eastward movement of the VSCS ‘Nargis’ is discussed to understand the features associated with such an unusual track of ‘Nargis’. Finally, the capability of the WRF model to predict the cyclone track of ‘Nargis’, which was really a recurved one and thus more difficult, is discussed in the present study. Some of the diagnostic features, which are observed in association with the unusual movement of ‘Nargis’ is also presented in the WRF model forecasts. A brief description about the WRF model used is given in section 2. Section 3 discusses the salient features of ‘Nargis’. The thermodynamical

and dynamical features associated with the recurrence of the system 'Nargis' along with some comparisons with earlier cyclones are discussed in section 4. The results of WRF model forecasts on real time basis are discussed in section 5 and all the results are summarized in section 6.

2. WRF modeling system and the real time model experiments

First the NCAR version 2.2 of Advanced Research WRF (ARW) model has been used. The model domain consists of 0° to 30°N and 65°E to 105°E with a horizontal resolution of 27 km and 28 vertical sigma levels. The initial conditions for the real data cases are preprocessed through a separate package called standard initialization (SI). The output from SI is passed to preprocessor in ARW, which generates initial and lateral boundary conditions. The SI is set of programs that takes terrestrial and meteorological data and transforms them for input to ARW preprocessor program for real data cases. In the present experiments, the real time analysis field obtained from the Global Forecasting System (GFS), NCEP USA with one degree resolution is used as initial and 6-hourly forecast files as boundary conditions. For the diagnostic study the NCEP FNL analysis at $1^{\circ} \times 1^{\circ}$ grid is used during the cyclone period of 'Nargis' from 27 April to 3 May 2008.

2.1 Overview of the WRF (ARW) model used in the present study

Dynamics	Nonhydrostatic
Model domain	0° – 30°N , 65° – 105°E
Horizontal grid distance	27 km
Integration time step	60 s
Map projection	Mercator
Horizontal grid system	Arakawa-C grid
Vertical co-ordinate	Sigma co-ordinates 28 σ levels
Time integration scheme	Third-order Runge–Kutta scheme
Spatial differencing scheme	Second to Sixth order schemes
Radiation parameterizations	RRTM, Dudhia scheme
Surface layer parameterizations	Monin–Obukhov scheme, thermal diffusion scheme
Cumulus parameterization	Grell–Devenyi ensemble
PBL parameterization	YSU scheme
Microphysics	WSM 3 simple ice scheme

The cumulus convection used in this case is modified Grell scheme (Grell–Devenyi scheme; Grell and Devenyi 2002), which was found to be better for the cyclone case using the WRF model. The G–D scheme is an expansion from the Grell convective parameterization (Grell 1993) to include several alternative closure assumptions that are commonly used in convective parameterizations. The unique aspect of the G–D scheme is that it uses 16 ensemble members derived from five popular closure assumptions to obtain an ensemble-mean realization at a time and location. These ensemble members are chosen because statistically they give a large spread in terms of accumulated convective rainfall. The details of how to determine the ensemble mean can be found in Grell and Devenyi (2002). The cloud microphysics scheme is WRF Single-Moment (WSM) 3-class simple ice scheme, which is a simple efficient scheme with ice and snow processes suitable for mesoscale grid sizes (Hong *et al* 1998, 2004). It replaces NCEP 3 scheme. The long-wave radiation parameterization is the Rapid Radiative Transfer Model (RRTM) scheme, which is an accurate scheme using look-up tables for efficiency accounts for multiple bands, trace gases, and microphysics species (Mlawer *et al* 1997). The short-wave radiation scheme is as per the Dudhia scheme, which allows simple downward integration for efficient cloud and clear-sky absorption and scattering (Dudhia 1989). The Planetary Boundary Layer (PBL) parameterization is the Yonsei University Scheme (YSU), which is the next generation MRF–PBL. It is non-local-K scheme with an explicit entrainment layer and parabolic K profile in unstable mixed layer (Skamarock *et al* 2005). Similar experiments in the operational mode are also conducted by integrating the WRF model at a relatively higher horizontal resolution (20 km) for 72 h with the same initial conditions of 28, 29, 30 and 1 May 2008 keeping all other options same as in the case of 27 km resolution.

3. A brief description of the very severe cyclonic storm (VSCS) 'Nargis'

Under the World Meteorological Organisation (WMO) definition about the tropical weather disturbances (table 1) has been adopted based on the maximum sustained wind speed when the system lies over sea area. Thus, when the maximum sustained wind exceeds 33 knots it is declared as a cyclone and when it exceeds 63 knots it is identified as very severe cyclonic storm (VSCS).

The system 'Nargis' initially appeared as a low-pressure area over southeast Bay of Bengal on 26 April and concentrated into a depression at 0300 UTC of 27 April. The observed track of

the VSCS ‘Nargis’ is shown in figure 1. As seen from figure 1, the system slightly moved north-westwards and intensified into a depression and then into a cyclone at 00 UTC of 28 April over southwest and adjoining southeast and westcentral Bay of Bengal about 550 km east of Chennai. The system remained practically stationary for some time and further intensified into an SCS at 09 UTC of 28 April and into a VSCS at 0300 UTC of 29 April over west central and adjoining southwest and southeast Bay of Bengal. The system moved slightly to the north and then eastwards for a period of about 30 h from 0600 UTC of 1 May till 1500 UTC of May towards the Myanmar coast and crossed the coast of Myanmar between 1730 and 1930 h IST on 2 May 2008 as a ‘VSCS’ (figure 1). The intense cloud band associated with the system on 2 May at 06 UTC is shown in figure 2. Even after the landfall the system was maintaining its intensity as a VSCS for a period of about 12 h. The VSCS ‘Nargis’ devastated large parts of

the low-lying delta region of the Irrawaddy River. Winds exceeded 190 kmph as the storm ripped through the Myanmar’s biggest city Yangon (estimated population 6 million) for over more than ten hours. Homes were flattened, more sturdy structures damaged, trees uprooted and power lines downed. In rural parts of the country up to 95% of all homes were destroyed. In the history of Myanmar it had never faced such a disastrous weather system in past 40 years.

4. Dynamical and thermodynamical features of VSCS ‘Nargis’

The genesis of such an intense system and forecasting of its unusual track is very challenging. The diagnostic study will give some characteristic features about the system associated with this unusual track. Before we discuss the results of WRF experiments the following dynamic and thermodynamic parameters are analysed to study the unusual movement of the VSCS ‘Nargis’.

4.1 Lower level (850 hPa) vorticity and vorticity advection

According to the atmospheric dynamics, the cyclone motion can be best represented by barotropic vorticity equation in this form:

$$\frac{\partial \xi}{\partial t} = -\vec{V} \cdot \nabla \xi - (\xi + f) \nabla \cdot \vec{V} + v \frac{\partial f}{\partial y},$$

where ‘ ξ ’ is the relative vorticity, ‘ $\vec{V}$ ’ is the horizontal wind vector, ‘ v ’ is the meridional wind

Table 1. *Classifications of intensity of cyclonic systems over the north Indian Ocean.*

Intensity of the system	Maximum sustained surface winds (knots) at sea (1 knot = 0.5144 ms ⁻¹)
Low pressure area	< 17
Depression	17–27
Deep depression (DD)	28–33
Cyclonic storm (CS)	34–47
Severe cyclonic storm (SCS)	48–63
Very severe cyclonic storm (VSCS)	64–119
Super cyclonic storm	> 119

Figure 1. Twelve hourly track of the cyclone ‘Nargis’ (12 UTC of 27 April to 00 UTC of 3 May 2008).

Figure 2. INSAT satellite picture of cyclone 'Nargis' at 0600 UTC of 2 May 2008.

component (positive towards north), and ' f ' is the coriolis parameter. The maximum cyclonic vorticity is at the centre and decreases with increasing radius. Hence, if the cyclone is moving in a given direction, the local rate of change of cyclonic vorticity given by the left-hand side term of the above equation must also increase in the same direction. The 850 hPa vorticity associated with the system from 28 April 00 UTC to 2 May 12 UTC is shown in figure 3. In the case of the VSCS 'Nargis', it was observed that vorticity increased in the easterly/east-northeasterly direction suggesting recurvature and moved in easterly/east-northeasterly direction (figure 3). The vorticity maximum of the order of $60 \times 10^{-6} \text{ s}^{-1}$ on 28 April was situated around $12.5^\circ\text{N}/85^\circ\text{E}$ (figure 3a) and this value gradually increases along the east/east-northeastwards direction on 2 May (figure 3e, f) to a value of the order of $210 \times 10^{-6} \text{ s}^{-1}$.

The above vorticity change can only be achieved by the processes represented by the term in the right-hand side of the equation. The advection of relative vorticity ($-V \cdot \nabla \xi$); where ' ξ ' represents for relative vorticity governs the motion of the cyclone. The tropical cyclone generally responds like a protected symmetric vortex in a uniform non-interacting fluid flow and the flow simply advects the vortex along it. This fact was also evident in the case of cyclone 'Nargis', considering the relative vorticity advection (figure 4.) with east/northeast ward shift of region of negative vorticity advection particularly from 1 May onwards (figures 4 d, e and f). The relative vorticity advection suggested east/east-northeast movement of the embedded vortex.

4.2 Upper level (200 hPa) winds

The upper level winds at 200 hPa during the period from 28 April to 3 May 2008 at 00 and 1200 UTC are shown in figure 5(a-f) to highlight the role of steering current. As it is seen from figure 1, the system was stationary for one day from 00 UTC of 28 to 00 UTC of 29 April and moved in northerly direction during next 12 h (till 12 UTC of 29) and subsequently recurved and moved in eastward direction. It is evident from the upper level flow that the system was under the influence of mainly the upper level southerly flow on 29 morning (figure 5b) and the recurvature of the system was associated with southerly/southwesterly flow from 30 April to 1 May (figure 5c and d). Thus, the recurvature of the system was associated with southerly/southwesterly wind at steering level (200 hPa level) over the east-central Bay of Bengal and adjoining areas. The system was also under the influence of upper level anticyclonic flow situated on southeastern sector of the centre of the system on 30 April and 1 May (figure 5c and d) and the ridge line was quite south of the system position (figures 5c-f). This feature was helpful in recurving the system from its normal northwesterly track. As discussed earlier by Srinivasan and Ramamurthy (1973) the position of the ridge line at 200 hPa is seen to govern the movement to a large extent. When the centre is near the ridge line, there is a northerly motion. Till the storm crosses the ridge line the movement continues in the northerly direction; when the centre is north of the ridge line as in the case of 'Nargis', in the majority of the cases a dominant easterly component of motion appears and thus, the system had a very long eastward movement.

4.3 Sea surface temperature (SST) and convection (OLR)

The SST was favourable (29°C or more) over west-central and adjoining east-central Bay of Bengal from 28 April onwards (figure not shown), which is a favourable condition for the intensification of the system. Further it may be seen that there was a warm pocket of SST anomalies (figure not shown) lies over west-central and adjoining east-central Bay of Bengal from 28 April onwards, which gradually concentrated over the Myanmar coast over east/east-northeast sector of the system centre from 30 April onwards. The presence of warm SST anomalies to the east/east-northeast sector of the system centre might have contributed to move the system towards the region of warm anomalies. Similar to the SST anomalies the minima in outgoing longwave radiation (OLR) anomaly (more negative values) also lay over the region to

Figure 3. 850 hPa relative vorticity in (10^{-6} s^{-1}) during different stages of the cyclone Nargis from 28 April to 2 May 2008.

the east/northeast of the system centre from 28 April to 3 May (figure 6). The centre of OLR minima moved eastward from 29 April onwards. Richie *et al* (1993) have also shown that meso-scale convective systems are present in all stages of tropical cyclones besides enhancing the rainfall activity, they influence the tropical cyclone motion as well. In case of 'Nargis' from 30 April 2008 onwards the centre of OLR minima lies to the east of the cyclone centre and hence contributes to the eastward movement (figure 6c–6f). As the

OLR minima correspond to the region of maximum convection, the monitoring of the convection centres (OLR minima) can give some useful guidance in predicting the movement of the cyclonic storm. However, to be used as an indicator for the movement of the system the resolution of the OLR data should be much higher than that used in the present case ($2.5^\circ \times 2.5^\circ$ latitude-longitude grid), which can fix the centre of convection anomalies more accurately with respect to the centre of the system.

Figure 4. 850 hPa horizontal vorticity advection (in 10^{-10} s^{-2}) during different stages of recurved cyclone 'Nargis' during 2008.

4.4 24-h pressure change

The 24 h mean sea level pressure change for this cyclonic storm over the Indian region during 28 April to 3 May 2008 are analysed and presented in figure 7. The 24 h pressure change indicates a large negative value in the eastern/northeastern sector (towards the Myanmar coast) of the system on 2 May with a value of the pressure fall of the order of 8 hPa (figure 7e). There is consistent 24 h pressure fall in the eastern/east-northeastern direction from the system centre during 30 April to 3 May

(figure 7c–7f). Thus, the VSCS 'Nargis' followed the direction of maximum negative isallobaric gradient and moved in the east/east-northeast direction as suggested in the cyclone manual (IMD 2003).

4.5 Comparison of diagnostic parameters of 'Nargis' with that of past cyclones

Some of the diagnostic parameters as discussed earlier in case of cyclone 'Nargis' is compared with that of previous two cyclones. The VSCS

Figure 5. The upper level winds over Indian region at 200 hPa as per NCEP reanalysis at different times between 28 April and 2 May 2008.

‘Nargis’ was having T number 5 and it crossed the Myanmar coast between 12 and 14 UTC of 2 May 2008. The two cyclones considered for comparison are (a) the super cyclonic storm of 25–31 October 1999 that crossed the Orissa coast on 29 October between 0430 and 0630 UTC with T number of 7 and the other one is (b) the very severe cyclonic storm ‘SIDR’ over Bay of Bengal during 11–16 November 2007 that crossed the Bangladesh coast between 15 and 18 UTC of 15

November with T number of 6. The low level relative vorticity, 24 h pressure change and the OLR anomalies on the respective date of crossing of coasts of these two cyclones are shown in figure 8. The observed 24-hourly track of the super cyclone and that of the VSCS ‘SIDR’ is superposed in figure 8(a) (26–30 October 1999) and in figure 8(d) (12–16 November 2007) respectively in the vorticity maps. The low level vorticity in case of VSCS ‘Nargis’ on the day of crossing is of the order

Figure 6. The OLR anomalies (watts/m²) over Indian region as per NCEP reanalysis at 00 UTC of 28 April to 3 May 2008 (a)–(f).

of $210 \times 10^{-6} \text{ s}^{-1}$ as shown in figure 3(e and f), which is of the same order in case of Orissa super cyclone as shown in figure 8(a). However, in case of the VSCS 'SIDR' the low-level vorticity is of the order of $150 \times 10^{-6} \text{ s}^{-1}$ (figure 8d). The 24 h pressure fall as in case of VSCS 'Nargis' on 2 May (the date of crossing) is of the order of 7 to 8 hPa to the east of the system (figure 7e), which is of the order of 4 hPa on 3 May (figure 7f), thus have very strong isallobaric gradient. In case of Orissa super cyclone and VSCS 'SIDR' the 24 h pressure

fall is of the order of 4 hPa in the forward direction of the system (figure 8b and e). The faster east/east-northeastly movement of VSCS 'Nargis' on 1 May (day before the landfall) compared to that of other two cyclones could be due to the strong isallobaric gradient in case of 'Nargis' on 2 May. The convection anomalies as represented by the negative OLR anomalies are of the order of 150 watts/m² in case of VSCS 'Nargis', which is of the same order of that of Orissa super cyclone (figures 6e and 8c). However, the negative OLR

Figure 7. The 24 h mean sea level pressure change over Indian region at 00 UTC of 28 April to 3 May 2008 (a)–(f).

anomalies in case of VSCS ‘SIDR’ is of the order of 125 watts/m^2 . On the other hand, the mean OLR (figure not shown) in case of ‘Nargis’ is lowest ($\approx 110 \text{ watts/m}^2$) compared to that of Orissa super cyclone ($\approx 135 \text{ watts/m}^2$) and the VSCS ‘SIDR’ ($\approx 150 \text{ watts/m}^2$), which indicates that the very strong deep convection noticed in case of ‘Nargis’ just like that of the Orissa super cyclone. Thus, the vorticity and OLR anomalies indicate that the VSCS ‘Nargis’ and the Orissa super cyclone are of comparable characteristics and the VSCS ‘SIDR’ is found to be a relatively weaker system.

5. Real time forecast of VSCS ‘Nargis’ using high resolution WRF model

5.1 Forecasts run of ‘Nargis’ with WRF model (27 km resolution)

The real time track forecast of the VSCS ‘Nargis’ using WRF V2.2 model at 27 km resolution starting from the initial conditions of 28 April to 1 May at 00 UTC is shown in figure 9 and the corresponding Direct Positional Errors (DPE) are calculated as the geographical distance between

Figure 8. Parameters for Orissa super cyclone of October 1999 and that of cyclone 'SIDR' of November 2007. (a) 850 hPa Relative vorticity in (10^{-6} s^{-1}) on 29 October 1999, (b) 24 h pressure change on 29 October 1999, (c) OLR anomalies on 29 October 1999. (d) to (f) same as (a) to (c) but for the cyclone 'SIDR' on 15 November 2007. 24 hourly observed track from 26–30 October 1999 is superposed in (a) and that of 12–16 November 2007 in (b).

the observed and forecast point (table 2). Like the observed track of 'Nargis' as shown in figure 1, the WRF model forecast based on 28 April initial condition (figure 9) also clearly indicated that the system was not going to hit the Indian coast. The 12 hourly forecast track error of the cyclone as given in table 2 based on the initial date of 28 April is found to be within the range of 235 km till 60 h of its forecast and the error increased to 349 km

in 72 h as the forecast track showed northeasterly movement (figure 9) compared to the easterly track in the observed case (figure 1). Based on the initial condition of 29 April, when the system was relatively strong (severe cyclonic storm) the initial error is about 17 km (table 2) and the corresponding forecast errors also reduced substantially. The real time forecast using 29 April initial condition also shows no land fall till 00 UTC of 2 May.

Figure 9. Initial and 24 h, 48 h and 72 h forecast positions of very severe cyclone 'Nargis' using WRF model at 27 km resolution with initial conditions of 28, 29, 30 April and 1 May 2008.

Table 2. Analysis errors, forecast errors and landfall errors of track forecast of cyclone 'Nargis' based on initial conditions of 28 April to 1 May 2008 using WRF model run at 27 km resolution.

Initial cond. → Errors ↓	28 April 00 UTC	29 April 00 UTC	30 April 00 UTC	1 May 00 UTC	Mean error (km)
00 h Anal error (km)	56	17	100	124	74
12 h FC error (km)	101	138	138	89	116
24 h FC error (km)	144	89	138	133	126
36 h FC error (km)	233	131	153	140	164
48 h FC error (km)	220	155	108	148	158
60 h FC error (km)	227	158	96	—	160
72 h FC error (km)	349	128	97	—	191
Landfall error (km)	No landfall	No landfall	85	50	—

However, the 72 h forecast position shows that the system was expected to hit the Myanmar coast as it followed the east/east-northeastward movement (figure 9) like that of observed track shown in figure 1. The forecast based on the initial condition of 30 April also shows east/east-northeastward movement of the cyclone till 72 h and was almost over the Myanmar coast in its 72 h forecast position (figure 9) and crossed the coast in its 78 h forecast position (figure not shown). Based on 30 April initial condition the forecast and observed tracks (figures 1 and 9) showed east/east-northeast movement of the system, although the forecast track showed slow movement compared to that of observed speed. The 12 hourly forecast error based on 30 April initial condition as given in table 2 is basically due to the slow movement of the system although it had a very similar track to that of the observed track. It is also indicated from figure 9 that the forecast tracks are improved with the initial conditions of 29 April to 1 May with landfall

error of 85 km and 50 km based on the initial condition of 30 April and 1 May, respectively. The mean initial error and 12 hourly mean forecast errors found from the WRF model runs (28, 29, 30 April and 1 May initial conditions) as given in table 2 is found to be less than 165 km till 60 h, which became 191 km for 72 h.

5.2 Forecasts run of 'Nargis' with WRF model (20 km resolution)

The WRF model is also run operationally in the hindcast mode for the VSCS 'Nargis' at a relatively higher resolution (20 km) starting from the initial conditions of 28 April to 1 May at 00 UTC and are given in figures 10–13 respectively. The 850 hPa wind for the analysis field along with the forecast winds valid at 24 h, 48 h and 72 h are shown starting from the initial condition of 28 April (figure 10) to 1 May (figure 13). The forecast track of 'Nargis' is also superposed in the diagram of

Figure 10. 850 hPa wind of WRF analysis and 3 days forecast wind fields. (a) Analysis based on 28 April initial condition with 72 h forecast track, (b), (c) and (d) corresponds to 24 h, 48 h and 72 h forecast wind fields.

analysis field in figures 10(a), 11(a), 12(a) and 13(a) based on 28, 29, 30 April and 1 May initial conditions, respectively. In rest of the figures the corresponding observed position of the VSCS 'Nargis' is marked with a closed circle to compare with the forecast positions. Based on the 12 hourly forecast positions of all four days, the DPEs are calculated and are given in table 3.

As it is seen from figure 10, the presence of a cyclonic vortices is represented in the initial model analysis field (figure 10a) although the exact position of the system is 35 km northeast of the analysis position and thus, has some analysis error as given in table 3. Hence the initial genesis of the system was captured in the WRF analysis field on 28 April, when the system was over the southwest

and adjoining southeast and west-central Bay of Bengal about 550 km east of Chennai. Like the observed track of 'Nargis' as shown in figure 1, the model forecast based on 28 April initial condition also clearly indicated that the system was not going to hit the Indian coast (figure 10a) and likely to move in northeasterly direction. It also indicates that there will be no landfall till 1 May 00 UTC. The forecast errors of the cyclone at 24 h, 48 h and 72 h as given in table 3 based on the initial date of 28 April is found to be 73 km, 116 km, and 244 km respectively. Based on 29 April initial condition when the system was relatively strong (severe cyclonic storm) the initial position as well as the forecast positions (figure 11) for 72 h forecast was very close to each other with initial error

Figure 11. 850 hPa wind of WRF analysis and 3 days forecast wind fields. (a) Analysis based on 29 April initial condition with 72 h track forecast. (b), (c) and (d) corresponds to 24 h, 48 h and 72 h forecast wind fields with indicated observed position.

of 41 km (figure 11a and table 3) and the forecast errors at 24 h, 48 h and 72 h are found to be 100 km, 80 km and 88 km, respectively. The error during 24 h is found to be more than that during 48 h and 72 h basically due to very slow movement of the system during first 24 h in the forecast field compared to that of the observed track (figure 11b), whereas, the relatively faster movement during the subsequent hours as seen in the observed track in figure 1 is well captured in the forecast fields at 48 h and 72 h (figure 11c and 11d). The real time forecast using 29 April initial condition also shows no land fall till 00 UTC of 2 May, however, the 72 h forecast position shows that the system was close to the Myanmar coast as it followed the east/east-northeastward

movement (figure 11) like that of the observed track shown in figure 1. The forecast based on the initial condition of 30 April also shows east/east-northeastward movement of the cyclone till 72 h and was close to the Myanmar coast in its 72 h forecast position (figure 12). Comparing the forecast track based on 30 April (figure 12a) with that of the observed track (figure 1) it is seen that both the tracks showed east/east-northeast movement of the system, although the forecast track showed slow movement compared to that of observed speed. The forecast errors at 24 h, 48 h and 72 h are found to be 53 km, 145 km, and 200 km respectively, whereas the analysis error and 12 h forecast error are higher on this day (93 km and 120 km, respectively). It is basically due to deviation in the

Figure 12. 850 hPa wind of WRF analysis and 3 days forecast wind fields. (a) Analysis based on 30 April initial condition with 72 h track forecast. (b), (c) and (d) corresponds to 24 h, 48 h and 72 h forecast wind fields with indicated observed position.

initial position of WRF analysis field and subsequent slow movement of the system during next 12 h (figure not shown). The landfall error is about 30 km (figure 12 and table 3) with the WRF model run at 00 UTC of 30 April (which is more than 60 h before the actual landfall time). Similarly, the initial condition of 1 May also showed eastward movement of the system towards the Myanmar coast like that of observed track (figure 13). The landfall error was about 40 km in this case. As seen from table 3, though the landfall errors are very less (30 km and 40 km) based on 30 April and 1 May initial conditions the forecast error at 48 h is of the order of 145–150 km, which is basically

due to relatively slow movement of the systems in the forecast field compared to that of observed track as shown in figure 1 and as a result there was a delay in landfall timing by about 10 h in the forecast tracks. It is also noticed from tables 2 and 3 that with the increase in horizontal resolution from 27 km to 20 km the forecast errors on individual day and also the mean forecast errors from four days of integrations have been reduced. Thus, it is very clear that the advanced version WRF model in the real time forecast run had captured very well the movement of the VSCS 'Nargis' almost 72 h in advance with very less forecast error.

Figure 13. 850 hPa wind of WRF analysis and 3 days forecast wind fields. (a) Analysis based on 1 May initial condition with 48 h track forecast. (b), (c) and (d) corresponds to 24 h, 48 h and 60 h forecast wind fields with indicated observed position.

5.3 Analysis of diagnostic fields from the WRF model (20 km resolution) forecast

As shown here the model has captured the eastward movement of cyclone reasonably well (figures 10–13). From the diagnostic analysis of the movement of VSCS ‘Nargis’ discussed earlier, it is observed that the recurvature of the system was associated with upper level southerly/ southwesterly wind at steering level (200 hPa level) over the east central Bay of Bengal and the adjoining areas. From the 24 h mean sea level pressure change it is also noticed that the VSCS ‘Nargis’ followed the direction of maximum negative isallobaric gradient and moved in the east/east-northeast direction.

Thus, it will be very interesting to see whether the diagnostic features observed in the reanalysis is also simulated well in the model. For that purpose the upper level steering wind at 200 hPa level and the MSLP change at different forecast hours in the forecast fields from WRF model are shown in figures 14 and 15, respectively. It is seen from figure 14 that the 48 h forecast valid on 30 April (figure 14a), that valid on 1 May (figure 14b) and the 72 h forecast that valid on 2 May (figure 14c) show the influence of upper-level southerly/southwesterly wind on cyclone, which indicated the easterly component of the movement of cyclone ‘Nargis’. Figure 14(d–f) also indicates southerly/southwesterly forecast wind valid

Table 3. Analysis errors, forecast errors and landfall errors of track forecast of cyclone 'Nargis' based on initial conditions of 28 April to 1 May 2008 using WRF model run at 20 km resolution.

Initial cond. → Errors ↓	28 April 00 UTC	29 April 00 UTC	30 April 00 UTC	1 May 00 UTC	Mean error (km)
00 h Anal error (km)	35	41	93	117	72
12 h FC error (km)	84	81	120	91	94
24 h FC error (km)	73	100	53	130	89
36 h FC error (km)	150	106	155	130	135
48 h FC error (km)	116	80	145	150	123
60 h FC error (km)	154	148	188	–	163
72 h FC error (km)	244	88	200	–	177
Landfall error (km)	No landfall	No landfall	30	40	–

for 1 and 2 May, which can be responsible for the eastward movement of the cyclone noticed in the model forecast. Just like in case of observation field (figure 5) the forecast fields also show presence of anticyclone circulation to the south of the system. Similarly, the forecast MSLP change (figure 15a–15f) at different hours also indicate pressure fall (of the order of more than 4 hPa) to the east of the system and hence the cyclone followed the direction of maximum negative isallobaric gradient and moved in eastward direction.

5.4 Discussions of the results

Over the years there have been improvement in the track forecast of tropical cyclone by numerical models. It may be mentioned that during the past three decades, forecast track errors from numerical prediction systems have decreased by approximately 25% at 24 h, 35% at 48 h and 50% at 72 h in the Atlantic basin (McAdie and Lawrence 2000). The 12 hourly mean forecast track error from the four days run (28 April to 1 May) as shown in tables 2 and 3 are much less than the mean forecast errors over the north Indian Ocean by different models (Gupta 2006). As summarized in a recent article by Gupta (2006), the mean forecast errors by Quasi-Lagrangian Model (QLM) run at 40 km resolution for 20 tropical cyclone cases over north Indian Ocean region for the seven-year period (1998–2004) is found to be 140 km for 24 h, 202 km in 48 h and 315 km for 72 h. The mean track forecast errors from the UK Met Office (UKMO) global model for three seasons prior to northern summer 2002 for the north Indian Ocean is found to be 130 km (54 cases) for 24 h, 220 km (36 cases) for 48 h, 313 km (20 cases) for 72 h, 305 km (11 cases) for 96 h and 278 km (6 cases) for 120 h (Gupta 2006). Similarly the mean forecast error from the NCMRWF T-80 global model from the six tropical cyclones of north Indian Ocean during 1995–96 using the bogus vortex in the initial

field is found to be 132 km for 24 h, 418 km for 48 h and 594 km for 72 h (Gupta 2006). Although the mean forecast errors obtained in case of the VSCS 'Nargis' in WRF model are much less as compared to the mean forecast error from QLM and other global models, a detailed statistics of WRF model will have to be considered by taking more number of cases to prepare the error statistics to make a proper comparison. The different physics and dynamic options available in the advanced version of WRF model can be considered for the preparation of detailed statistics, which is planned to be carried out in a separate study.

In the case of VSCS 'Nargis' the different numerical models have performed differently in the real time. As seen from the verification of track forecast by the UK Met Office global model for the VSCS 'Nargis' (obtained from forecast verification of tropical cyclone track forecast from UKMO site <http://www.metoffice.gov.uk/weather/tropicalcyclone/tctracks>) the 120-hour prediction of landfall was good, whereas the 96-hour forecast was poorer. This pattern was repeated for shorter lead time forecasts. The model had a right of track bias, which meant that many forecast tracks took 'Nargis' south of the Irrawaddy Delta of Burma. However, 24–36 h ahead of landfall, the forecasts were good. The landfall error as estimated from the forecast charts of UKMO model based on the initial conditions of 30 April (60 h before the landfall) and 1 May (36 h before the landfall) was found to be around 150 km and 110 km, respectively with a time delay of about 4–5 h. The performance of ECMWF global model for the case of VSCS 'Nargis' was much closer to the observed track with estimated landfall errors of less than 50 km based on the initial conditions of 30 April (60 h before the landfall) and 1 May (36 h before the landfall) with an estimated 7 h early landfall. The QLM model run operationally in IMD showed large error in case of VSCS 'Nargis' with landfall error of more than 300 km based on initial conditions of 30 April and 1 May (60 h and 36 h

Figure 14. 200 hPa forecast wind over Indian region from WRF (2.2) model run for the cyclone 'Nargis' from different initial date from 28 April to 1 May. (a) 48 h forecast wind of 28 April at 00 UTC (valid for 30 April) and the black closed circle indicates the 48 h forecast position of Nargis valid for 30 April. Similar descriptions for the other figures.

before the landfall). The official forecast (consensus forecast) issued by IMD at 06 UTC on 1 May (36 h in advance of landfall) indicated the landfall error of 110 km and landfall time error of $3\frac{1}{2}$ h. Similarly the landfall error was 110 km 24 h in advance and 55 km 12 h in advance with landfall time error of

1–2 h. As part of the Regional Specialised Meteorological Centre (RSMC) responsibility under the World Meteorological Organisation (WMO) IMD had provided an advance information of landfall of 'Nargis' in Myanmar prior to 36 h. The same was appreciated by the WMO.

Figure 15. The 24 h mean sea level pressure change over Indian region from WRF model run for the cyclone of 'Nargis' from different initial date from 28 April to 01 May. (a) 72–48 h forecast MSLP of 28 April at 00 UTC (valid for 1 May MSLP–30 April MSLP at 00 UTC) and the black closed circle indicates the 48 h forecast position of 'Nargis' valid for 30 April. Similar descriptions for the other figures also.

6. Conclusions

The following broad conclusions are drawn from the above results and discussion.

The VSCS 'Nargis' over the east-central Bay of Bengal had a very long easterly movement for a period of about 30 h from 06 UTC of 1 May till 15 UTC of 2 May before hitting the

coast of Myanmar. The easterly/east-northeasterly movement of the VSCS 'Nargis' was mainly due to (i) upper level southerly/southwesterly steering wind at 200 hPa level over the region associated with presence of an anticyclone in the southeast of the system centre; (ii) higher SST (29°C or more) over the region to the northeast of cyclone centre with positive anomalies in the east/northeast

sector; (iii) large negative 24 h pressure change to the east of the storm centre; (iv) large vorticity maximum to the east of the centre of the system.

The real time track forecast using the WRF model at 27 km and 20 km resolution based on the initial conditions of 28 April (when the system was only 550 km away from the Indian coast) indicated that the system was not expected to cross the Indian coast. Similarly, based on 29 April initial condition the system showed east/east-northeasterly movement towards the Myanmar coast. The east/east-northeasterly movement of the 'Nargis' was persisting in the forecast based on 30 April and 1 May initial conditions with landfall error of 85 km and 50 km in with 27 km resolution, which reduces to 30 km and 40 km in WRF model with 20 km resolution respectively with a landfall time delay of about 10 h. Thus, it is very clear that the advanced version WRF model in the real time forecast had captured very well the movement of VSCS 'Nargis' reasonably well almost 72 h in advance with very less forecast error. Consistence with the diagnostic analysis the WRF model forecast also indicates southerly/southwesterly strong steering wind at 200 hPa level and maximum pressure fall to the east of the system. Although the mean forecast errors obtained in case of the VSCS 'Nargis' are much less as compared to the mean forecast error from QLM and other global models, more number of cyclone cases have to be considered to prepare mean errors from the WRF model using different physics and dynamic options to make a proper comparison.

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