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Advance forecasting of cyclone track over north Indian Ocean using a global circulation model

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सार – उष्णकटिबंधीय चक्रवात समूचे विश्व में अधिकांश तटवर्ती क्षेत्रों में गंभीर और विकराल डर उत्पन्न करते रहते हैं। इसलिए उष्णकटिबंधीय चक्रवातों के संबंध में अधिक सटीक और लम्बी अवधि के पूर्वानुमान की माँग बढ़ती जा रही है। यद्यपि काफी समय से सीमित क्षेत्र निदर्श (एल. ए. एम.) उष्णकटिबंधीय चक्रवातों के गतिकीय पूर्वानुमान के लिए परम्परागत साधन रहे हैं फिर भी इस बात से भी इंकार नही किया जा सकता है कि चक्रवातों की गतिकीय प्रकृति के प्रस्तुतीकरण में भूमंडलीय परिसंचरण निदर्शों (जी. सी. एम.) के उपयोग के फल स्वरूप काफी सुधार आया है। उदाहरण के लिए बंगाल की खाड़ी के कुछ चक्रवात तो बंगाल की खाड़ी में ही विकसित होते हैं किंतु बहुत से चक्रवात खाड़ी के पूर्व की तरफ बने निम्न दाब क्षेत्र के सघन होने और खाड़ी की ओर बढ़ने के कारण बनते हैं जिससे यह स्पष्ट है कि चक्रवात के पूर्वानुमान के लिए चक्रवात के उत्पन्न होने के विस्तृत क्षेत्र को शामिल करने की आवश्यकता है। इस शोध–पत्र में हमने बताया है कि एल. ए. एम. और जी. सी. एम. की संयुक्त विशेषता तुलनात्मक रूप से नवीन श्रेणी के भूमंडलीय मॉडलों (जी. सी. एम.) से चक्रवात के मार्ग और उसकी तीव्रता जैसे कुछ अत्यंत महत्वपूर्ण लक्षणों के संबंध में लम्बी अवधि के और अधिक सटीक तरह के पूर्वानुमान दोनों उपलब्ध करा सकते हैं। सात चक्रवातों से संबंधित विभिन्न स्थानों, ऋतुओं, वर्ष और उनकी तीव्रता, प्रतिरूपित मार्गों और चक्रवातों के लैंडफाल के स्थलों के पाँच दिनों से भी अधिक समय पहले की उनकी आरंभिक अवस्थाओं और उनके संबंध में समुद्र सतह तापमान (एस. एस. टी.) के मासिक जलवायु विज्ञान के 48 घंटे पहले जारी किए गए हैं। इनमें तात्कालिक प्रचालनात्मक पूर्वानुमान के समान ही त्रुटियाँ पाई गई हैं।

ABSTRACT. Tropical cyclones pose a serious and growing threat to many coastal areas world over; there is increasing demand for better accuracy as well as longer range for tropical cyclone forecasts. While the traditional tool for dynamical forecasting of tropical cyclones has been Limited Area Models (LAM), there are reasons to believe that use of Global Circulation Models (GCM) may result in improved representation of cyclone dynamics. Over Bay of Bengal, for example, while some cyclones develop *in situ*, many result from intensification of low pressure system that travel from the east, implying need for consideration of a large domain. We show here that a relatively new class of Global Circulation Models (GCM), combining the advantages of LAMs and GCMs, can provide both longer range and better accuracy for such critical parameters like track and intensity. For seven cyclones representing different locations, seasons, years and strength, simulated tracks and land-fall locations show, with initial condition more than 5 days ahead and only monthly climatology of sea surface temperature (SST), errors comparable to those from current operational forecast 48 hours in advance.

Key words – Track forecasting, Global circulation models, Bay of Bengal cyclones, Variable resolution GCM.

1. Introduction

While there has been considerable progress in modeling and forecasting of cyclones over the past decades, there is also a growing expectation and demand for longer range and higher accuracy (Bengtsson 2001). The most widely used tool for dynamical forecasting of tropical cyclones is the so called LAMs or meso-scale models: three dimensional models of the atmosphere defined over a domain much smaller than the global domain. While a LAM can afford very high resolution over a domain of interest, not yet feasible in GCM, it requires artificial lateral boundary conditions which have to be supplied externally and which can greatly limit its performance. Besides, LAM cannot incorporate the effects of larger (than domain) scale circulations except through the lateral boundary conditions. Leaving aside the issue of required resolution, there are reasons to believe that a global model would provide a better platform for tropical cyclone simulation and forecasting, especially to address

TABLE 1

Description of the experiments

Label	Type	Genesis location	Duration	Initial state	Zoom centre
M97	VSCS	9.0,90.5	15-20 May	15 May	15,90
S97	SCS	15.5,82.5	23-27 Sep	22 Sep	15,90
J98	VSCS	11.0,69.0	4-10 Jun	4 Jun	15,65
N98	VSCS	13.5,86.5	19-22 Nov	17 Nov	15,90
M99	VSCS	14.5,70.5	16-22 May	15 May	15,65
O99	VSCS	13.0,95.0	25-29 Oct	20 Oct	15,90
N00	VSCS	10.0,90.0	26-30 Nov	25 Nov	15,90

issues like growing demand for longer lead (AMS Council, 2000) and interaction of a cyclone with large scale circulation. A tropical cyclone is a small but an intense part of the global circulation, affecting many scales of motion; there is growing evidence that the large scale circulation features have considerable effect on the smaller scale circulation (Tanguay, *et al.* 1995). For issues like response of genesis and intensification of cyclones to large scale systems like El Nino or an altered climate, a global model is certainly a better candidate (Vitart and Anderson 2001).

In case of the Bay of Bengal cyclones, while some develop *in situ* others intensify from low-pressure systems that migrate from the east, (Vitart *et al.* 2002) thus implying need for considering dynamics over a rather wide domain. There have been attempts and some success in simulating tropical cyclones using GCM (Vitart and Anderson 2001 ; Bengtsson, *et al.* 1995 ; Zhang and Krishanamurti, 1997); these studies demonstrate the power and potential of GCM in studying tropical cyclone. However, to qualify as a forecasting tool a GCM must also possess sufficient forecasting skill at required resolution.

A relatively new class of GCM that combines the advantages of a GCM and a LAM to a large extent are the so called Variable Resolution GCM which allows a higher resolution (zoom) over a specified domain. In a complex system like a GCM, there is a close interplay between numeric and physics; it has been shown that model performance is quite sensitive to model resolution (Boyle, 1993). Introduction of a zoom, for example, changes and can allow more realistic scale interaction. In the tropics, and in the case of intense convective systems like a tropical cyclone, a zoom can significantly alter the model dynamics. While the resolution attained in a variable resolution GCM may still be coarse compared to that in an LAM, we expect that the other advantages of a GCM,

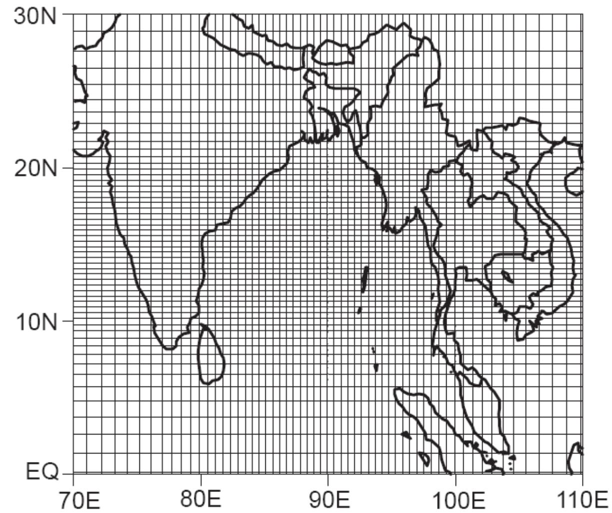

Fig. 1. Structure of a variable resolution grid with the centre of the zoom over 15° N, 90° E. The highest resolution near the centre of the zoom is about 50 km × 40 km in longitude and latitude, respectively

such as global dynamics, will result in improved simulation. The purpose of the present work is to explore the success of this approach in a number of cases of observed cyclone.

To design our experiments, we note that tropical cyclone formation has a strong seasonality that varies from one basin to another. For the Bay of Bengal the occurrence of tropical cyclones has a secondary maximum in May and a primary maximum in the October-November period (Frank, 1987). Here we report seven simulations, chosen to include different seasons, different years and different regions. Table 1 provides a quick summary of the various experiments; here VSCS stands for Very Severe Cyclonic Storm.

2. Model and the experiments

We have adopted the version LMDZ 3.3 of the variable-resolution GCM developed at the Laboratory for Dynamic Meteorology, Paris. The basic features of the model have been described in a number of works (Sadourny and Laval, 1984 and Sharma and Sadourny, 1986). Fig. 1 shows a part of the model grid around the centre of the zoom over the Bay of Bengal. The highest resolution (near the centre of the zoom) is about 0.5° × 0.4° in longitude and latitude, which merges uniformly to 2° in longitude and 1.25° in latitude away from the zoom.

The number of vertical levels used is 19. The present version includes a land-surface model and a diurnal cycle. The convection parameterization scheme is that of Tidke (Tiedtke, 1993).

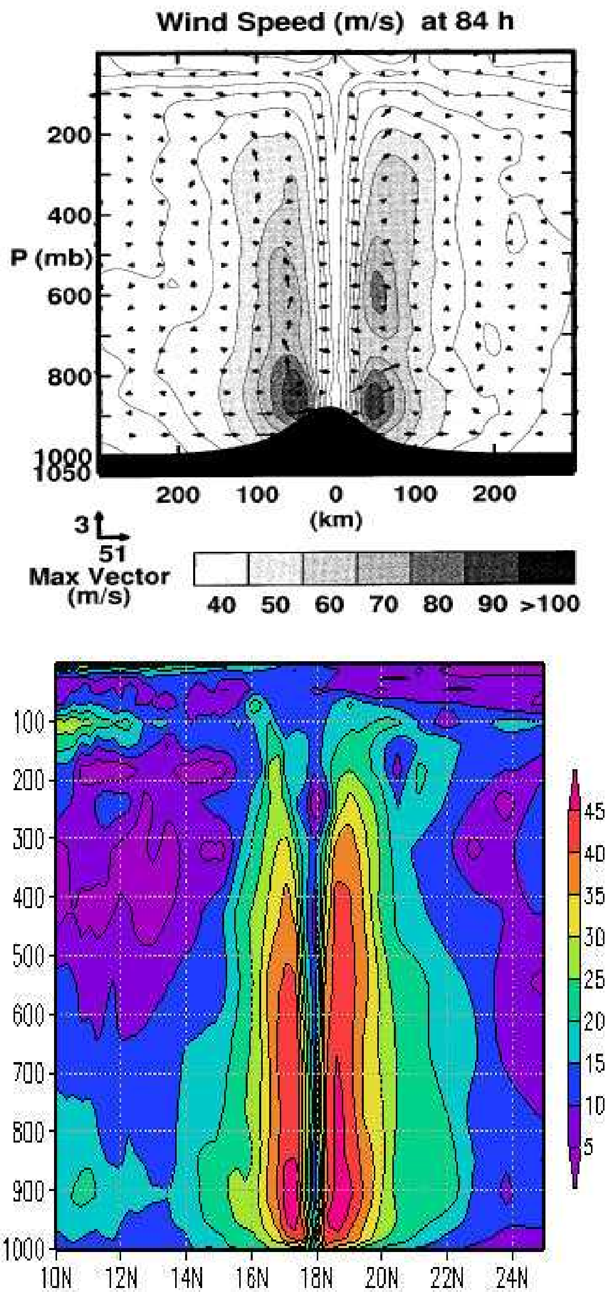

Fig. 2. Comparison of wind structure in vertical cross-section view. Top panel is from MM5 simulation (Frank and Ritchie, 2001) and Bottom panel is from GCM simulation (at 66 hour)

To examine the forecast potential of the methodology, we use only monthly climatological SST from Atmospheric Model Intercomparison Project (AMIP). The initial states as well as the surface temperature fields were prescribed from daily data available from National Center for Environmental Prediction, USA (NCEP) Reanalysis, interpolated to the model grid. However, we shall present one case, the super cyclone that hit Orissa in November, 1999, using initial condition and SST from a different dataset, *viz*., European Centre for Medium Range Weather Forecasts (ECMWF) daily analysis available on 1° × 1° grid to examine the robustness of the procedure.

We first present, in Fig. 2, a comparison of the longitude-height structure of simulated wind field from a meso-scale model (MM5), adopted from (Frank and Ritchie, 2001) and the VR-GCM (Bottom panel). The MM5 simulations were carried out using a 3-nest grid with the highest resolution in the inner most grid of about 5 km; the VR-GCM simulations, as mentioned above, has resolution of about 50 km × 40 km in longitude and latitude near the centre of the zoom. The simulations have similarities as well as differences. The meso-scale simulation shows a more detail vertical structure near the centre but very little structure off-centre; the GCM simulation, on the other hand, shows a richer structure of the dynamical fields. Overall, however, both the simulations capture the typical structure of a cyclone quite well.

3. Results

A huge amount of diagnostics is possible with model fields available over a global domain. Our focus here is simulation of tracks and intensity, the most difficult yet the most useful parameters in tropical cyclone forecasting. However, we shall show the evolution of the spatial structure of two important dynamical fields for two cases, each representing one of the basins. Further, these two cyclones represent two different categories of cyclones in the north Indian Ocean in terms of genesis: while one developed *in-situ*, the other intensified from a low-pressure system that traveled from the east.

Fig. 3 shows the simulated fields of surface pressure and low-level vector winds for the cyclone that hit Gujrat in May 1999 (M99). The genesis of the system as a loosely organized low-pressure system around 70° E, 14° N is seen on 19 May. Apart from the clear northward movement of the cyclone, a very interesting feature is the formation of two other systems during the period 20-22 May 1999, both of which subsequently decayed, while the original system intensified to a cyclone. It is well known that out of a number of low-pressure systems only a few intensify to cyclonic strength. The regional climatology of cyclones over the north Indian Ocean shows that only six out of average 16 disturbances per year intensify to tropical storms and less than half of these storms intensify to cyclones. The sufficiency conditions that govern this selection are still an outstanding problem in tropical

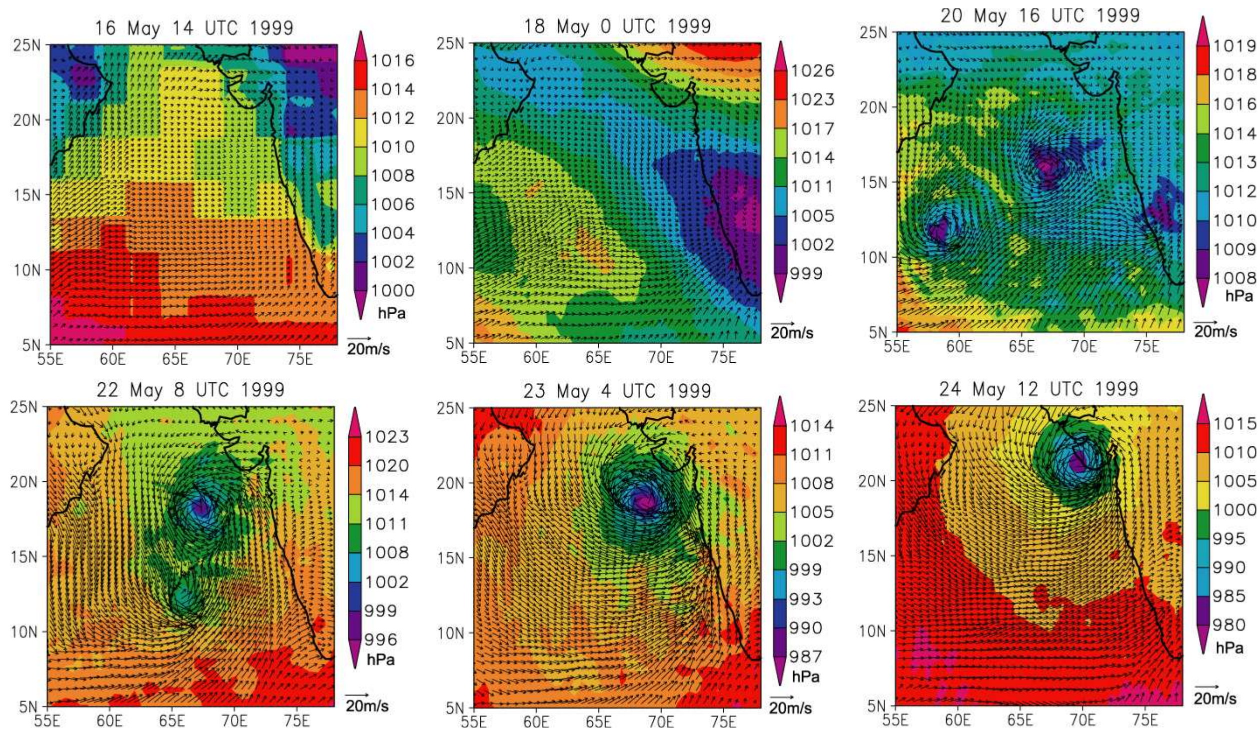

Fig. 3. Simulated fields of surface pressure and vector wind for the May 1999 Gujarat cyclone, with initial condition from NCEP analysis for 16 May, 1999

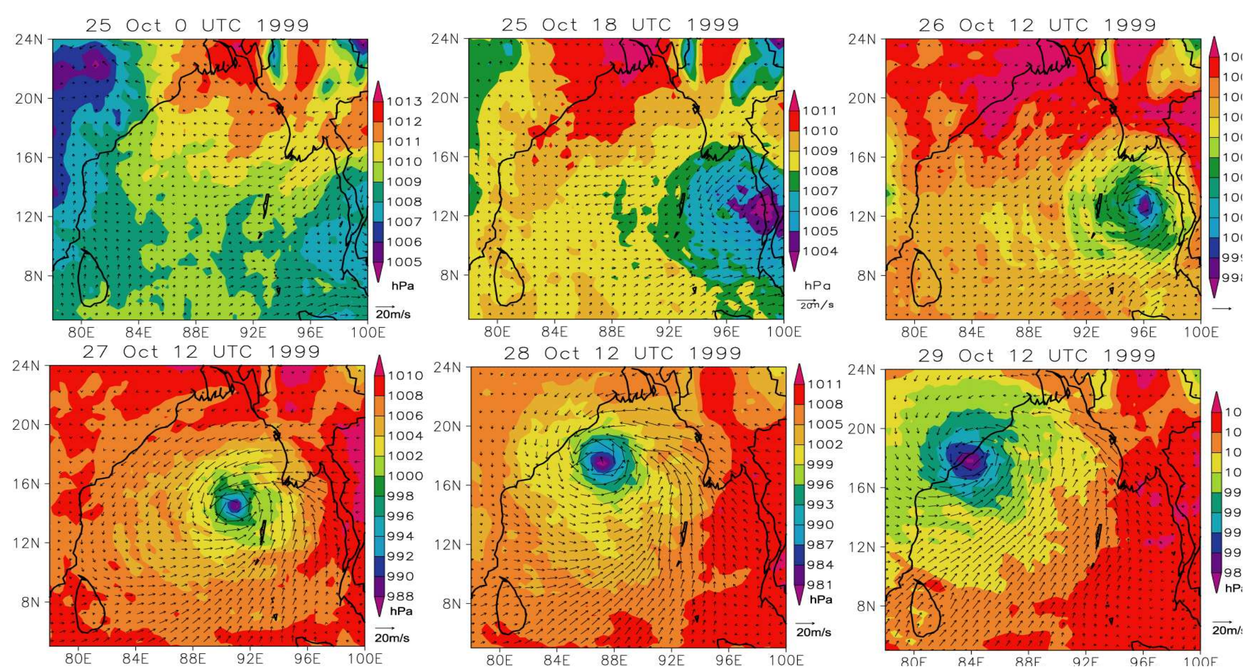

Fig. 4. Simulated fields of surface pressure and vector wind for the October 1999 Orissa Super Cyclone, with initial condition from ECMWF analysis for 20 October 1999

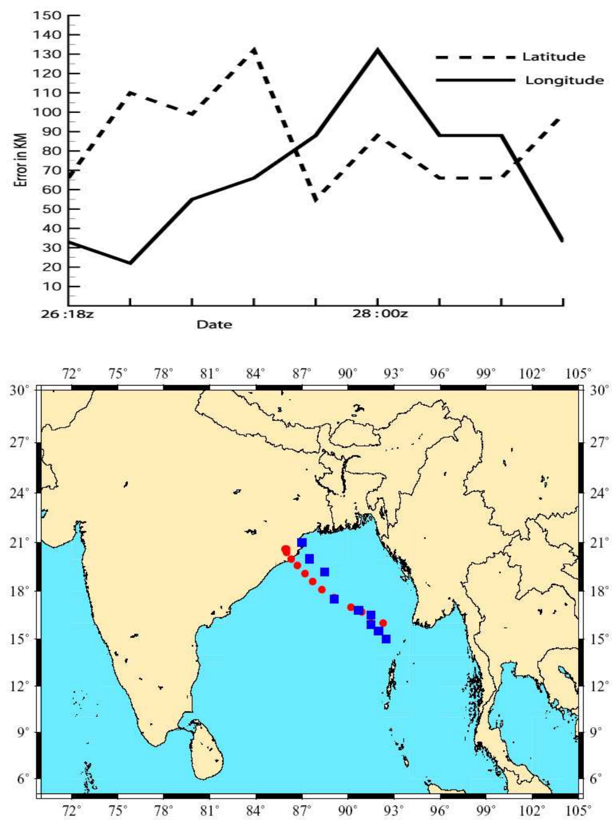

Fig. 5. Track forecast error in terms of (absolute) difference between longitudes and latitudes of minimum sea-level pressure from model forecasts and the location of the centre of the cyclone from observation (IMD) at 6-hourly intervals. The somewhat large error in the initial time is essentially a result of identification problem during the formative stage of the cyclones, when several systems may co-exist

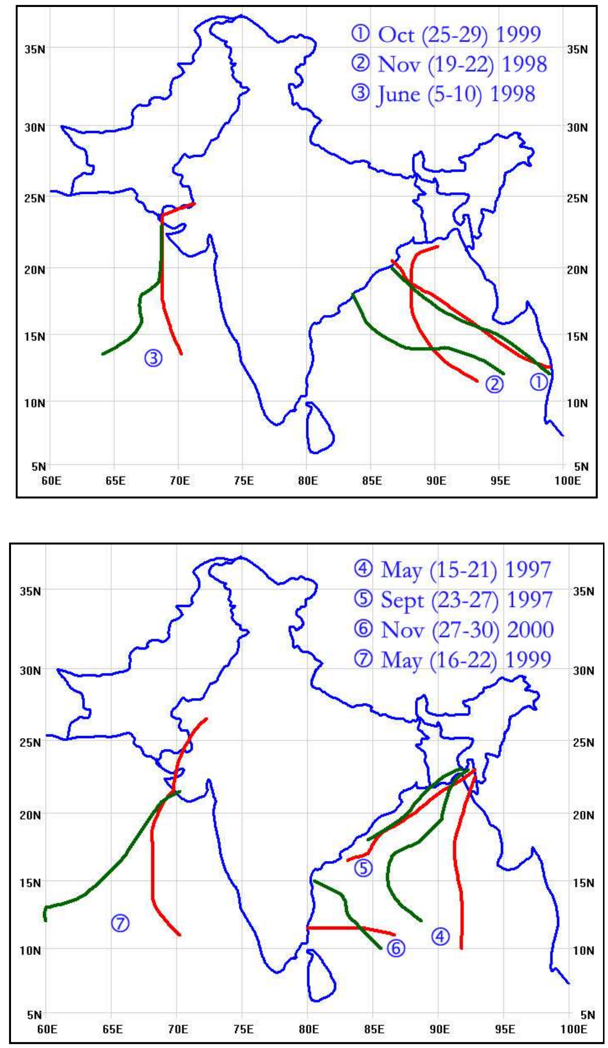

Fig. 6. Comparison of simulated track (green) and observed (red, IMD) for 7 cyclone cases

cyclone dynamics. While the dynamics and the thermodynamics that led to the genesis of multiple systems and the subsequent selective intensification can be unraveled only through a systematic study involving a large number of sensitivity experiments, the model's ability to generate such features is encouraging. However, this needs to be evaluated statistically.

The M99 cyclone was an example of a cyclone that developed *in situ*. We next consider a system that apparently travelled from the east and intensified : the super cyclone that hit Orissa in October, 1999. The simulated results for this cyclone presented below are with initial conditions from ECMWF analysis for 20 October, 1999. The results with initial conditions from NCEP analysis for this cyclone are discussed later in this work. The comparison of simulated and the observed tracks (Fig. 6) show very good agreement in most of the cases. The simulated fields of surface pressure and low-level vector winds are presented in Fig. 4.

The simulation shows the disturbance travelling from the east and moving in the north-west-north direction as it intensified. Fig. 5 examines the performance of the model in forecasting the track in terms of errors in latitude and longitude as function of forecast time. The relatively larger errors in the genesis stage of the track may have contribution from ambiguity in identifying the system at very early (weak) stage, when multiple, weak systems may coexist.

The average errors in land-fall locations in our simulation is 1.35° in longitude and 1.1° in latitude. However, for a strict comparison, our simulation statistics have to be considerably enlarged.

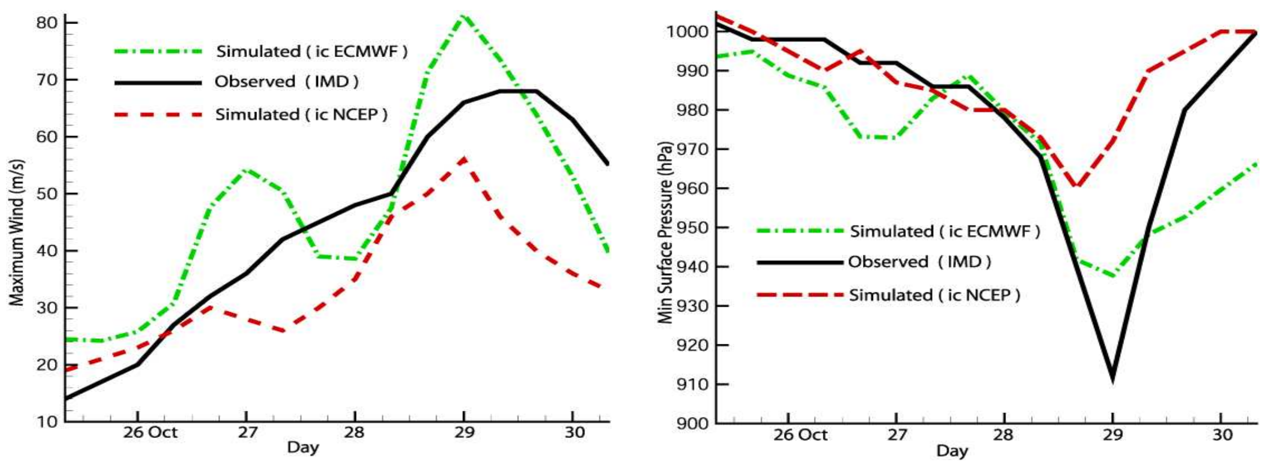

Fig. 7. Time evolution of maximum wind (m/s) (left panel) and minimum surface pressure (hPa) (right panel) for the super cyclone of Orissa with ECMWF (green line) and NCEP (red line) initial condition; the black line indicates observation (IMD)

TABLE 2

Comparison of observation and simulation

Case	Δ Pc		Max wind		Land-fall*	
	Obs (hPa)	Sim (hPa)	Obs (m/s)	Sim (m/s)	Obs Lat., Long.	Sim Lat., Long.
M97	35	40	66	42	22.5,92.0	22.0,92.0
S97	16	13	18	24	22.0,91.0	23.0,91.0
J98	38	18	52	26	21.5,69.0	21.0,67.0
N98	16	14	25	20	21.0,89.0	18.0,84.0
M99	54	28	54	30	24.0,67.5	23.5,66.5
O99	82	61	70	54	20.0,86.0	19.5,86.0
N00	22	14	54	20	11.5,80.0	12.5,80.0

* Latitude in degree north, Longitude in degree east.

Δ Pc denotes the difference between environmental (about 1000 km away from the position of lowest surface pressure) and the lowest surface pressures in hectapascal (hPa)

4. Statistical evaluation

While the ability of the model to simulate many aspects of two cyclones over different locations is encouraging, a statistical evaluation of the model skill is imperative to asses reliability and the margins of error. We present here a limited sample analysis by considering seven cyclones that occurred over in north Indian Ocean in different years and in different seasons (May/October). As the parameter for evaluation, we consider the track and the intensity, the most challenging tasks in tropical cyclone forecasting track. This, along with the time and the location of the landfall, are also the most important quantities for efficient management of cyclone-related hazard.

Table 2 lists the seven cases considered in this study along with a comparison of observed and simulated parameters like central pressure drop, intensity and landfall location. Fig. 6 compares the simulated track (green) with the corresponding observed (red, IMD) for the seven cyclones. For the M97 case, there is a gross departure in the middle of the simulation, although there is very good agreement for the landfall location. If the particular case of November 1998 is not included, the average error for the six cases is 1.1° in longitude and 0.45° in latitude with a lead time of about more than 150 hours. It is worth mentioning that the case of November 1998 cyclone considered here is a rather special as it was preceded by a cyclone in the same locality. In comparison, the error in the National Hurricane Center Track forecast is 1.5° for a 24-hour forecast and nearly twice that for a 48-hour forecast (AMS, 2000 and Bengtsson, 2001).

5. Impact of initial state

It is well known that, at least for short-term forecasts, initial state plays a dominant role. To obtain a first glimpse of this effect, we had carried out the simulation of the October 1999 Orissa super cyclone also with initial conditions from NCEP analysis. The simulation is done with initial condition of 25th October, 1999 with the same setup mentioned earlier. The comparison is shown in Fig. 7; it is very evident that maximum wind and minimum surface pressure are simulated better with ECMWF initial conditions. Similar conclusions also hold for errors in track forecasting; in particular, error in landfall with NCEP initial condition is much larger than corresponding error with ECMWF initial condition (Fig. 5).

6. Conclusions

Two strong points of the present simulations are considerably longer lead and relative low error in track and land-fall forecast. Indeed, in our case errors in 7 day simulations (*i.e.*, initial conditions 7 days before landfall) were often smaller than 5 days simulations. This is attributed to error in the (low-resolution) initial condition closer to the time of genesis which can contaminate the simulation. On the other hand, the model appears to be able to generate correct dynamics with an initial state away from the genesis. The consistent performance of the model for different conditions with only climatological SST makes it an attractive tool for tropical cyclone forecasting. In an actual application one could generate multiple forecasts, each for an ocean basin, with a grid that has been critically evaluated for the basin. Further improvement through higher resolution, better choice of schemes etc. is possible and is under investigation.

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Supplementary Informations:

Further results from the simulations are available from the corresponding author.

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