ORIGINAL PAPER

Prediction of tropical cyclone trajectories over the Northern Indian Ocean using COSMO

Freddy P. Paul[1,2] · D. Bala Subrahamanyam[1]

Abstract

The present study investigates the performance of a regional numerical weather prediction model; namely, the Consortium for Small-scale Modelling (COSMO) in the prediction of the tropical cyclone (TC) trajectories for varying intensities of the storm. A total of 8 TCs formed over the Northern Indian Ocean from 2017 to 2019 are chosen for the evaluation of the COSMO model. The central pressure ($P_{Central}$), pressure drop (ΔP), and maximum sustained surface wind speed (MSW) simulated by the COSMO model are validated against the concurrent observations from India Meteorological Department. The forecasted mean track errors are 95 km for a lead time of 24 h, whereas it was about 140 km for a lead time of 48 h. The mean initial positional error in identification of the storm was about 50 km. The intensity of a storm is underestimated in terms of ΔP and MSW, especially for a lead time of 0–24 h, whereas the model shows a consistent overestimation for a lead time of more than 24 h. During the initial stage of a storm, when its intensity is categorized as a Deep Depression, we notice a maximum amount of uncertainty in the prediction of cyclone track. The COSMO model yields improved predictability of the tracks for storms categorized as Very Severe Cyclonic Storms. As the intensity of a storm increases from a Deep Depression to a Very Severe Cyclonic Storm, the track errors associated with model simulations tend to decrease. Results of the present study illustrate the predictability of TCs from COSMO in terms of the trajectory and intensity of the storm.

1 Introduction

Tropical cyclones (TCs) are some of the most destructive and devastating natural hazards attracting timely attention of disaster management system. Accurate analysis of the intensity of a TC, its structure, and position is very much crucial, especially for those cases when these variables are consistently changing. The ability of numerical weather prediction (NWP) models to provide advanced forecasts of the trajectory and intensity of a TC helps in the protection of human lives and wealth by issuing appropriate and timely warnings. The regional NWP models serve as a primary tool for the operational weather forecasters in the identification of a low-pressure system over the oceanic basins as well as in the assessment of its movement, and probable landfall location. However, the prediction of a TC evolution depends on many factors at different scales, altitudes, and times, which makes the forecast of a TC track extremely complicated (Emanuel 2003). Because of its complexity, accurate prediction of the timing, location, and intensity of a TC remains an ongoing challenge. Therefore, a large group of weather forecasters are continuously striving to improve the predictability of TCs to reduce the human casualties and improve the disaster management system (Langmack et al. 2012; Cruz and Narisma 2016; Samiksha et al. 2017; Zhou et al. 2017; Subrahamanyam et al. 2019; Dube et al. 2020; Mohanty et al. 2020).

The Indian sub-continent surrounded by the North Indian Ocean (NIO), comprising the Bay of Bengal (BoB) on the eastern side, and the Arabian Sea (AS) on the western side is exposed to nearly 10% of the world's TCs, making it as one of the worst cyclone-affected regions (Dube et al. 2020). Among the global oceans, the track forecast errors over the NIO are relatively high in comparison to the Atlantic and the Pacific Oceans (Mohapatra et al. 2013). On an

---

✉ Freddy P. Paul
   ppfreddy89@gmail.com

1   Space Physics Laboratory, Vikram Sarabhai Space Centre, Department of Space, Government of India, Indian Space Research Organisation, Thiruvananthapuram, Kerala 695 022, India

2   Cochin University of Science and Technology, Cochin, Kerala 682 022, India

average, the NIO witnesses 5–6 TCs each year and offers a natural laboratory to the weather forecasters for investigation of different aspects of regional NWP models and their potential in the prediction of TCs (Dube et al. 1997; Singh and Bhaskaran 2018). Though the regional NWP models have the potential to provide advanced predictions of TCs, they need appropriate initial and lateral boundary conditions (LBCs) from the global models. Kumar et al. (2015) have compared the impact of four operational global model analyses from the European Centre for Medium-Range Weather Forecasts (ECMWF), National Centers for Environmental Prediction (NCEP) Global Data Assimilation System (GDAS), NCEP Global Forecasting System (GFS), and National Centre for Medium-Range Weather Forecasting (NCMRWF) on the performance of a regional atmospheric model namely, the Weather Research and Forecasting (WRF). Results from their study demonstrated improved performance of WRF model with the ECMWF analyses. Mukhopadhyay et al. (2011) carried out a sensitivity study on the impact of three different convection parameterization schemes in the prediction of the track and intensity of two TCs and addressed the problems associated with the incorporation of moist processes at different grid resolutions. Singh and Bhaskaran (2017) evaluated the performance of the Advanced Research Weather Research and Forecasting (WRF-ARW) model for prediction of BoB TCs by testing a combination of five Planetary Boundary Layer (PBL) and six cumulus convection parameterization schemes. Based on the "best possible" combinations of model physics used by Singh and Bhaskaran (2017), the predicted mean track error for a forecast lead time of 24 h was 71 km, whereas it was 114 km for 48 h. In one of the case studies, Bhaskar Rao et al. (2009) investigated the impact of horizontal grid resolution on the prediction of track and intensity of the Orissa Super Cyclone of 1999. In this study, an enhancement in the grid resolution of the mesoscale atmospheric model did not influence the track of the storm. Tang et al. (2020) have summarized recent advances in our understanding of tropical cyclogenesis involving the interaction of dynamic and thermodynamic processes at multiple spatio-temporal scales. In their review paper, they have described the interaction of intraseasonal and synoptic variability and the interaction of multiple environmental controls, such as the vertical wind shear, tropospheric moisture, sea, and surface temperature in cyclogenesis. The forecasting skill of NWP models has substantially improved in recent decades, which can be attributed to the data assimilation techniques, improved treatment of sub-grid scale processes, and enhanced meteorological measurements from ground-based and space-borne platforms (Mohanty and Gupta 1997; Singh et al. 2012; Ganesh et al. 2018; Dube et al. 2020).

Since the prediction of TC trajectories has received much attention, it is equally important to be aware of the intrinsic

and practical predictability limits of an NWP model in question for operational applications. Therefore, it is beneficial to evaluate the performance of an NWP model in terms of predictability of severe weather events such as TCs. In this regard, COnsortium for Small-scale MOdelling (COSMO) provides a reliable and flexible NWP model, which has got widespread applications in the spatial scales spanning from mesoscale to regional scales (Baldauf et al. 2011). Subrahamanyam et al. (2019) have carried out a case study on the performance evaluation of this model for one of the rarest very severe cyclonic storms, namely Ockhi, over the AS. Results obtained from their study indicated a track error of about 74 km for a lead time of 24 h, whereas it was about 41 km with a lead time of 18 h. Their study indicated an obvious dependence of the difference between the simulated and observed trajectory of Ockhi on the lead time. However, their study was confined to a single cyclone Ockhi which was one of the rarest TCs in the AS of the post-monsoon season.

The present study is focused on the performance evaluation of the COSMO model in the predictability of TCs over the BoB and the AS region for 8 TCs from 2017 to 2019. The main objectives of this work are twofold: (i) first, the COSMO model simulations are assessed for the identification of a TC, and thereafter, the behaviour of model-simulated cyclone trajectories is investigated depending on the forecasting lead time; (ii) second, the predictability of a TC for various intensities of a storm is explored in terms of the pressure drop (ΔP), the maximum sustained wind speed (MSW), and errors in the simulated trajectories of cyclones. With these objectives, the contents of this paper are organized into five sections. Sections 2 and 3 provide details about the COSMO model and the database used in the present study, respectively. Section 4 covers the broad features about the progression of 8 TCs. Section 5 highlights the results obtained from the model simulations in terms of predictability of TCs for varying intensities. Finally, Sect. 6 summarizes the important findings from this study with concluding remarks.

2 About the COSMO model

The Deutscher Wetterdienst (DWD, the German Weather Service) offers short-to-medium-range weather predictions with the help of ICOsahedral Non-hydrostatic (ICON), one of the global circulation models (Zängl et al. 2015). Following the same philosophy adopted in the ICON global model, DWD released a regional NWP model, namely COSMO, which has a similar model configuration, physics, and data assimilation schemes as that in the ICON. The primary goal of development of a regional model was to meet high-resolution forecast requirements in operational

weather predictions, and also to provide the user with a flexible tool for research mode applications. The first version of COSMO was released in 2007; and thereafter, new versions of this model are being regularly updated under the framework of a consortium for incorporating the latest updates in different modules of the model (Baldauf et al. 2011; Anurose and Subrahamanyam 2015; Subrahamanyam et al. 2019). In recent years, the COSMO has been extensively used for the prediction of numerous meteorological fields and assessment of severe weather events over different parts of the globe. For example, Shrestha et al. (2015) used the COSMO model to analyze a deep convective storm event over the north-western foothills of the Himalayas, which yielded about 200 mm of precipitation within a day on 13 September 2012. The spatial pattern of daily-accumulated rainfall and atmospheric state profiles simulated by COSMO during this event compared well with the satellite and radiosonde observations. During the international event of the Sochi-2014 Olympic Games, Murav'ev et al. (2015) carried out the verification of deterministic forecasts of precipitation, air temperature, and wind speed from the COSMO model. Kurowski et al. (2016) analyzed the mesoscale simulations from the COSMO model over the Alpine region, and showed a good agreement between the model simulations and observations for a typical westerly flow accompanied by a passage of frontal systems. Anurose and Subrahamanyam (2015) compared the altitude profiles of thermodynamic parameters of ABL simulated by the COSMO with the balloon-borne GPS sonde observations over Thiruvananthapuram, a coastal station in India. Results obtained from their study revealed a good agreement between the model-simulated ABL thickness with concurrent GPS sonde measurements. Fotso-Kamga et al. (2020) have illustrated the ability of the COSMO model in simulation of the observed precipitation, low-level wind circulation, and seasonal cycles of precipitation pattern over the Central African region. The model provides a flexible tool for meso-β and meso-γ scale applications. Table 1 summarizes the technical details of the COSMO model used in the present study.

In the present study, we have used version 5.05 of COSMO which was released in 2018. The governing equations of the model are based on the thermo-hydrodynamic equations in three-dimensional form and are numerically solved by second- or third-order finite difference methods on Arakawa-C-grid system. The lowest level of the model is placed at 10 m and a generalized terrain-following (sigma) height coordinate system is used for defining the vertical grid points (Schättler et al. 2018). The terrain-following coordinate system is very common in NWP models, though it has some inherent problems in geographical areas with steep topography. In a recent review, Mesinger and Veljovic (2020) have analyzed possible errors in approximations of the pressure gradient force over steep topography in

terrain-following coordinate systems. The COSMO model uses a generalized terrain-following height coordinate (sigma), where any unique function of geometrical height can be used for transformation. This coordinate system in vertical direction allows mapping the irregular grid associated with the terrain-following system in physical space onto a rectangular and regular computational grid. Thus, the model takes into account the impacts of topography on the organized convection and its penetration to high altitudes (Schättler et al. 2018). The model uses 51 vertical layers from the surface to a ceiling pressure coordinate of about 12.8 hPa roughly corresponding to 29.9 km. Approximately 17 levels are included in the lower atmosphere for addressing the atmospheric boundary layer processes between the surface to an altitude of 3 km. The model offers a choice of schemes for parameterization of sub-grid scale processes of radiation, surface layer, atmospheric boundary layer, soil processes, convection, and precipitation. Horizontal and vertical Cartesian wind components, temperature, pressure perturbation, specific humidity, turbulent kinetic energy, cloud water content, cloud ice content, the specific water content of rain, snow, and graupel are prognostic variables, while total air density, and precipitation fluxes of rain and snow are diagnostic variables of the model.

3 Database

The meteorological database used in the present study is categorized under two classes, namely, (i) the COSMO model simulations and (ii) the India Meteorological Department (IMD) Best Track data. More specifically, the central pressure (P_{Central}), ΔP, and MSW simulated by COSMO, together with the IMD observations constitute the main database in the present study.

3.1 COSMO model simulations

The initial and LBCs for the COSMO model simulations are derived from the analysis and forecast fields of the ICON global model, respectively. Here, we have used two different domains for the BoB and the AS cyclones. The BoB domain extends from 76° E longitude to 95° E longitude, while the AS domain is spread between 64° E longitude and 79° E longitude (see Fig. 1). In both these domains, the latitudinal coverage is kept identical between 4° N to 24° N. These domains cover the movement of individual TC from the stage of depression to final dissipation. For incorporating all the 8 TCs spanning from 2017 to 2019 within a uniform time-scale, the calendar day numbers associated with each of these cyclones are indexed from 1 to 49 and are referred to as the cyclone day numbers (see Table 2 for more details). On each of

Table 1 Technical description of the COSMO model used for the simulation of 8 TCs over the BoB and the AS region during 2017 to 2019

| Model domain and reference atmosphere	
Study domain	Indian peninsula and the adjoining Bay of Bengal and Arabian Sea
Longitudinal coverage:	1) 76° E−95° E for Bay of Bengal
	2) 64° E-78° E for AS domain
Latitudinal coverage:	4° N to 24 ° N
Horizontal grid resolution	0.0625 ° (~ 7 km)
Reference atmosphere	Default version of the COSMO
Parameters for the Model Run	
Initial conditions of atmosphere	Analysis fields corresponding to 00 UTC From ICON global model
Lateral boundary conditions (LBCs)	Forecast fields from ICON Global model at 3 h intervals
Forecast duration	48 h
Model time step	30 s
Numerical techniques for model run	
Grid structure	Arakawa-C-grid
Time integration	Two time level second- and third-order Runge–Kutta Scheme
Spatial discretization	Second-order finite difference technique
Numerical smoothing	Horizontal diffusion of fourth order
Parametrization of physical processes	
Soil processes	A two-layer soil model based on numerical solution Of heat conduction (Jacobsen and Heise 1982)
Surface-layer turbulent fluxes	New TKE-based scheme which includes laminar Sub-layer
Vertical turbulence diffusion	Prognostic TKE-based scheme including the effects Of sub-grid evaporation and condensation
Moist convection	Tiedtke (1989)
Radiation	Ritter and Geleyn (1992)
Grid-scale precipitation	Kessler-type warm scheme with cloud Ice and cloud water

Table 2 Details of the 8 TCs, their geographical region of genesis and category, and their respective indexed cyclone day numbers

Name of the tropical cyclone (TC)	Basin	Duration	Category of the storm attained	Cyclone day number
Marutha	BoB	15–17 Apr 2017 (3 days)	CS[1]	1–3
Mora	BoB	28–30 May 2017 (3 days)	SCS[2]	3–6
Ockhi	AS	29 Nov-6 Dec 2017 (8 days)	VSCS[3]	6–13
Titli	BoB	8-12- Oct 2018 (5 days)	VSCS[3]	13–18
Gaja	BoB	10–20 Nov 2018 (11 days)	VSCS[3]	18–28
Phethai	BoB	13–18 Dec 2018 (6 days)	SCS[2]	28–33
Fani	BoB	26 Apr-4 May 2019 (9 days)	ESCS[4]	33–42
Vayu	AS	10–17 Jun 2019 (8 days)	VSCS[3]	42–49

[1]Cyclonic storm (CS); [2]severe cyclonic Storm (SCS); [3]very severe cyclonic storm (VSCS); [4]Extremely severe cyclonic storm (ESCS)

these cyclone day numbers, the initial condition of atmosphere is extracted from the analysis of ICON global model corresponding to 00 UTC of the respective day and the COSMO model simulations are carried out for a period of
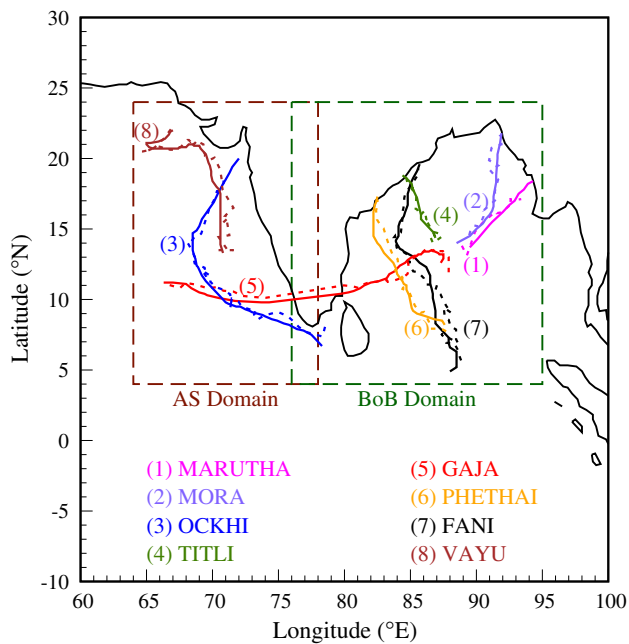
Fig. 1 Geographical model domain of the COSMO for the Arabian Sea and the Bay of Bengal region is depicted through two rectangular boxes. Also shown in the figure are observed (continuous) and predicted (dashed) trajectories of 8 TCs, namely (1) Marutha, (2) Mora, (3) Ockhi, (4) Fani, (5) Titli, (6) Gaja, (7) Phethai, and (8) Vayu. Observed tracks are taken from the India Meteorological Department's Best Track data

48 h each. Afterwards, the forecasted meteorological fields of pressure and wind speed are used for the determination of $P_{Central}$, ΔP, and MSW corresponding to an individual cyclone. Location of the eye of the storm is identified as the location corresponding to a minimum value of $P_{Central}$.

3.2 Observations from IMD

We have used the observational data from e-Atlas of the Regional Specialized Meteorological Centre (RSMC) of IMD for the validation of COSMO model simulations. The e-Atlas of RSMC provides details on the track of cyclones, intensity, movement, $P_{Central}$, ΔP, MSW, and other relevant information at 3-hourly intervals. The observed values of $P_{Central}$ are derived by an empirical relation suggested by Fletcher (1955). All these observations described in e-Atlas come through a variety of sources, including the surface networks, rawinsondes, radar, meteorological satellites, ship logs, and buoys (Mohapatra et al. 2011, 2012). Therefore, the uncertainties in the observed measurements can also lead to uncertainties in the validation of an NWP model. We have adopted the standard definitions of different categories of a TC based on the glossary of IMD (IMD-RSMC Frequently asked questions 2021).

4 TCs over the BoB and the AS during 2017–2019

Results obtained from the past literature reveals that the frequency of TCs is more over the BoB than the AS, primarily because of warm SSTs, with an approximate ratio being 4:1. The NIO experiences 5–6 TCs on an annual basis, with a primary maximum in TC frequency during the Post-monsoon season (October–December) and a secondary maximum during the Pre-monsoon season (April–early June) (Osuri et al. 2013; Bhatla et al. 2020). During 2017–2019, the NIO region witnessed a total of 31 depressions, out of which 20 were intensified into named cyclonic storms (CSs). Among them, 12 CSs were formed over the BoB region, and the rest of the 8 storms were in the AS region. In the present investigation, we have chosen a total of 8 CSs over the NIO region for evaluating the performance of the COSMO model in predictions of cyclone trajectories. Here, we present an overview of the 8 TCs under evaluation.

4.1 Marutha (15–17 April 2017)

Marutha was one of the short-lived weak CSs of the pre-monsoon season over the BoB. Its genesis started on 00 UTC of 15 April 2017 over the southeast BoB when depression was identified at 88.0° E/12.0° N location. On the same day, this system became a deep depression (DD) at 09 UTC and remained as a DD for 9 h, before intensifying into a CS at 18 UTC. Marutha remained as a CS for the next 24 h. Eventually, it weakened into a DD on 21 UTC of 16 April 2017 and dissipated into a well-marked low pressure on 17 April 2017 (Mishra et al. 2019). The trajectory of this CS is labelled as (1) in Fig. 1. During the passage of this storm, a maximum of 8 hPa ΔP and 20.5 m s^{-1} MSW was observed.

4.2 Mora (28–30 May 2017)

Mora was a Severe Cyclonic Storm (SCS) formed during the pre-monsoon season over the southeast BoB whose genesis started from the stage of depression on 00 UTC of 28 May 2017 at 88.5° E/14° N. Mora attained the status of a CS on the same day as it developed adequate pressure drop at 15 UTC. Under the favourable conditions, the storm sustained as a CS for the next 21 h and got intensified into an SCS on 12 UTC of 29 May 2017. Mora continued as an SCS and made the landfall on early morning hours of 30 May 2017 and dissipated into a well-marked low-pressure area (Chutia et al. 2019). The trajectory of Mora is labelled as (2) in Fig. 1. The maximum ΔP and MSW associated with this storm were reported as 18 hPa and 31 m s^{-1}, respectively.

4.3 Ockhi (29 November–6 December 2017)

Ockhi was one of the rarest CSs whose genesis took place near 81.8° E/6.5° N location in the Comorin Sea at 03 UTC on 29 November 2017. The Comorin Sea generally does not offer favourable conditions for the cyclogenesis, but Okchi originated from depression and intensified into a DD at 21 UTC of 29 November 2017. Since the formation of DD was close to equator and landmass, rapid intensification of the DD was not expected. However, after 6 h of its formation as a DD, the system intensified into a CS and eventually became a very severe cyclonic storm (VSCS) on 1 December 2017 (Roshny et al. 2018; Subrahamanyam et al. 2019, 2020). This long-lived storm travelled through a re-curvature track labelled as (3) in Fig. 1 and weakened into a well-marked low-pressure area over the northeast AS on 5 December 2017. The maximum value of ΔP and MSW for this storm were 34 hPa and 43.7 m s^{-1}, respectively.

4.4 Titli (8–12 October 2018)

Titli, a VSCS, was originated as a depression over central BoB near 88.8° E/14.0° N at 03 UTC on 8 October 2018. Initially, the system sustained as a depression for a few hours and became a DD at 18 UTC on the same day. Under favourable conditions for the cyclogenesis, the system attained the status of a CS at 06 UTC of 9 October 2018. Later, this was intensified into an SCS and then VSCS as it traversed towards the landmass [labelled as (4) in Fig. 1]. After making the landfall, the storm gradually dissipated and became a well-marked low pressure on 13 October 2018 (Nadimpalli et al. 2020). During the passage of this VSCS, the maximum ΔP was 32 hPa, whereas the MSW was as high as 41 m s^{-1}.

4.5 Gaja (10–20 November 2018)

Gaja was one of the long-lived VSCSs with a very longer time-span as well as the trajectory (Dube et al. 2020; Sharma et al. 2020). This storm was originated as a depression over the southeast BoB near 92.5° E/11.7° N at 03 UTC of 10 November 2018 and attained the status of a CS at 00 UTC of 11 November 2018. Furthermore, the progression of Gaja towards the landmass was reasonably slow and it continued as a CS for more than 4 days. As it approached the landmass, it was intensified into an SCS and then a VSCS at 21 UTC of 15 November 2018. Even after the landfall, this storm sustained for more time and crossed the peninsular Indian sub-continent and entered into the AS, where it weakened into a DD and then became a depression. On 19 October 2018, this storm lost all its intensity and became a well-marked low pressure over the central AS. A maximum of 30

hPa ΔP and the MSW of 36 m s^{-1} was observed during the passage of this storm. The trajectory of this storm is labelled as (5) in Fig. 1.

4.6 Phethai (13–18 December 2018)

Phethai, an SCS was originated as a depression over the southeast BoB close to 88.7° E/6.5° N at 00 UTC on 13 December 2018. As the system moved northward, it attained the favourable conditions for the cyclogenesis and became a CS at 12 UTC of 15 December 2018, and further intensified into an SCS at 09 UTC of 16 December 2018 (Dube et al. 2020). It remained as an SCS for the next 15 h, and as it approached the landmass, it started dissipating and eventually became a well-marked low pressure on 18 December 2018 [its trajectory is labelled as (6) in Fig. 1]. During the passage of this storm, a maximum ΔP of 15 hPa was observed, whereas the MSW magnitude was 28.2 m s^{-1}.

4.7 Fani (27 April–4 May 2019)

Fani was one of the rarest CSs of the pre-monsoon season with very rapid intensification. This storm was originated as a depression over the eastern equatorial Indian Ocean close to 89.7° E/2.7° N at 03 UTC of 26 April 2019. The system was intensified into a DD at 00 UTC of 27 April 2019, and within the next 6 h, it attained the status of a CS. Fani continued as a CS for 2 days and then intensified into SCS at 12 UTC of 29 April 2019. Later, it became a VSCS at 00 UTC of 30 April 2019 and sustained the status for nearly 3 days and then further intensified into an Extremely Severe Cyclonic Storm (ESCS). During the stage of landfall on 3 May 2019, its intensity was continuing as an ESCS, and thus, it led to serious damages over the landfall region (Kumar et al. 2020; Mohanty et al. 2020). During the passage of this storm, a maximum ΔP of 66 hPa was observed, whereas the magnitude of MSW was as high as 59 m s^{-1}. The trajectory of this storm is labelled as (7) in Fig. 1.

4.8 Vayu (10–17 June 2019)

Vayu, a VSCS was originated as a depression over central AS close to 71.0° E/11.7° N at 00 UTC of 10 June 2019. On the same day, this depression became a DD and further intensified into a CS at 18 UTC. The storm moved parallel to the west coast of Indian sub-continent and attained the status of an SCS at 12 UTC of 11 June 2019 [its track is labelled as (8) in Fig. 1]. It further intensified into a VSCS at 15 UTC on 12 June 2019 (Albert and Bhaskaran 2020). The system hovered over the AS for about 4 days and dissipated into a well-marked low-pressure area over the northeast AS. The

maximum value of observed ΔP and MSW for this storm was 32 hPa and 41.1 m s^{-1}, respectively.

5 Results and discussion

### 5.1 Prediction of cyclone trajectories for 8 TCs

In Fig. 2a–h, we present an individual assessment of the model-simulated trajectories for the 8 TCs as a function of the forecasting lead time. The model simulations are statistically evaluated by the mean error and the corresponding root-mean-square error. The mean error of the COSMO simulated track from observation and the RMSE values are depicted at 3 h intervals from 0 to 48 h. For individual cyclones, we have estimated the mean track error and RMSE by taking all the available simulations and corresponding observations from IMD. The first data point in all the 8 panels of Fig. 2a–h corresponding to 0 h lead time depicts the uncertainty in the initial conditions of atmosphere derived from the ICON model. In all the TCs under consideration in this investigation, the uncertainty in the initial position of the track was less than 70 km. In the case of Gaja cyclone, the initial position of the storm obtained from ICON was within a diameter of 20 km, whereas in a worst-case scenario, the initial position of the storm was more than 70 km away from the actual position for the Fani cyclone. Except for a few cases, the track error tends to increase with the forecasting lead time. In the case of Mora cyclone, the mean initial position error was as low as 20 km, but the predicted track deviates significantly from the IMD observations with forecasting lead time (Fig. 2b). The predicted trajectory of Mora with a lead time of 24 h was about 80 km, whereas the error was more than 200 km for a lead time of 48 h. In the case of Fani cyclone, the initial position itself deviated by more than 60 km, and despite having a large error in the initial position of the storm, the COSMO was able to predict its trajectory with a mean error of 80 km for a lead time of 24 h. The track error of Fani cyclone for a lead time of 48 h was 157 km, which is better than the Mora, Titli, and Ockhi where the initial position of the cyclone was better represented in the ICON analysis. There are few cases of TCs where the predicted trajectory for a storm showed significant errors from the observed trajectory despite having more accurate initial conditions in terms of the position of the storm, and hence, we can not attribute the errors in predicted trajectory by COSMO to the initial conditions alone. This also indicates that the predicted trajectory of a cyclone by COSMO depends on other factors in addition to the representation of the initial position of the storm.

For representing a composite picture on the mean variations in the model-simulated trajectory, we have prepared an ensemble of all the cyclones and have plotted the mean error in the predicted trajectory as a function of forecasting lead time in Fig. 3. From the composite track error plot, it is clear that the errors between the model-simulated trajectory and the observations increase with forecasting lead time. The analysis shows a mean track error of about 50 km for the initial position of the storm, whereas it increases to 95 km for a lead time of 24 h and further increases to about 140 km for a lead time of 48 h. Mohapatra et al. (2013) have investigated the performance of objective TC forecast for short-range for a period of 9 years spanning from 2003 to 2011, and have shown an average direct position error of about 140 km and 262 km for a lead time of 24 h and 48 h, respectively. In another study, Singh and Bhaskaran (2018) have investigated the track error for the TCs of 2013 and 2014 over the BoB region with the aid of WRF model, and have demonstrated that the mean track error is 65 km, 58 km, 99 km, and 103 km from day 1 to day 4, respectively. In their study, the initial positional error was 41 km. More recently, Dube et al. (2020) have carried out a detailed investigation on the performance of the operational global ensemble prediction system at the NCMRWF for a total of 13 TCs from 2016 to 2018, and have reported a track error of about 260 km for a lead time of 120 h, whereas it was about 140 km for a lead time of 48 h. In this context, the performance of COSMO is reasonably good as far as the prediction of cyclone trajectories with a lead time of 0–48 h is concerned.

5.2 Prediction of the intensity of TCs

To validate the performance of COSMO model simulations, we compare the simulated intensity of 8 TCs with simultaneous observations obtained from the e-Atlas of IMD. The simulated and observed magnitudes of $P_{Central}$, ΔP, and MSW for 8 TCs are plotted as a function of the Cyclone Day Numbers in three rows of Fig. 4a–c, respectively. Model simulations for each cyclone cover time-period from the stage of DD to the final dissipation. On each of the cyclone day numbers, model simulations were carried out for a duration of 48 h each. For discriminating the predictions valid for the first and second day, we have plotted the forecast parameters with a lead time of 0–24 h (the first day), and 24–48 h (the second day) in different colours in Fig. 4. Different categories of a TC in terms of the standard thresholds of pressure drop and MSW are marked by horizontal lines in Fig. 4b–c for quick referencing. Qualitatively, there is a fair agreement between the model simulations and observations in terms of $P_{Central}$ for a lead time of 0 to 24 h; however, there are large errors in the magnitude of $P_{Central}$ with a lead time of 24–48 h (Fig. 4a). The gross features in the temporal variation of $P_{Central}$ as well as ΔP observed by IMD are well reflected in the model simulations, but the differences between the simulated and observed magnitudes of $P_{Central}$ tend to increase for the most intense phase of a
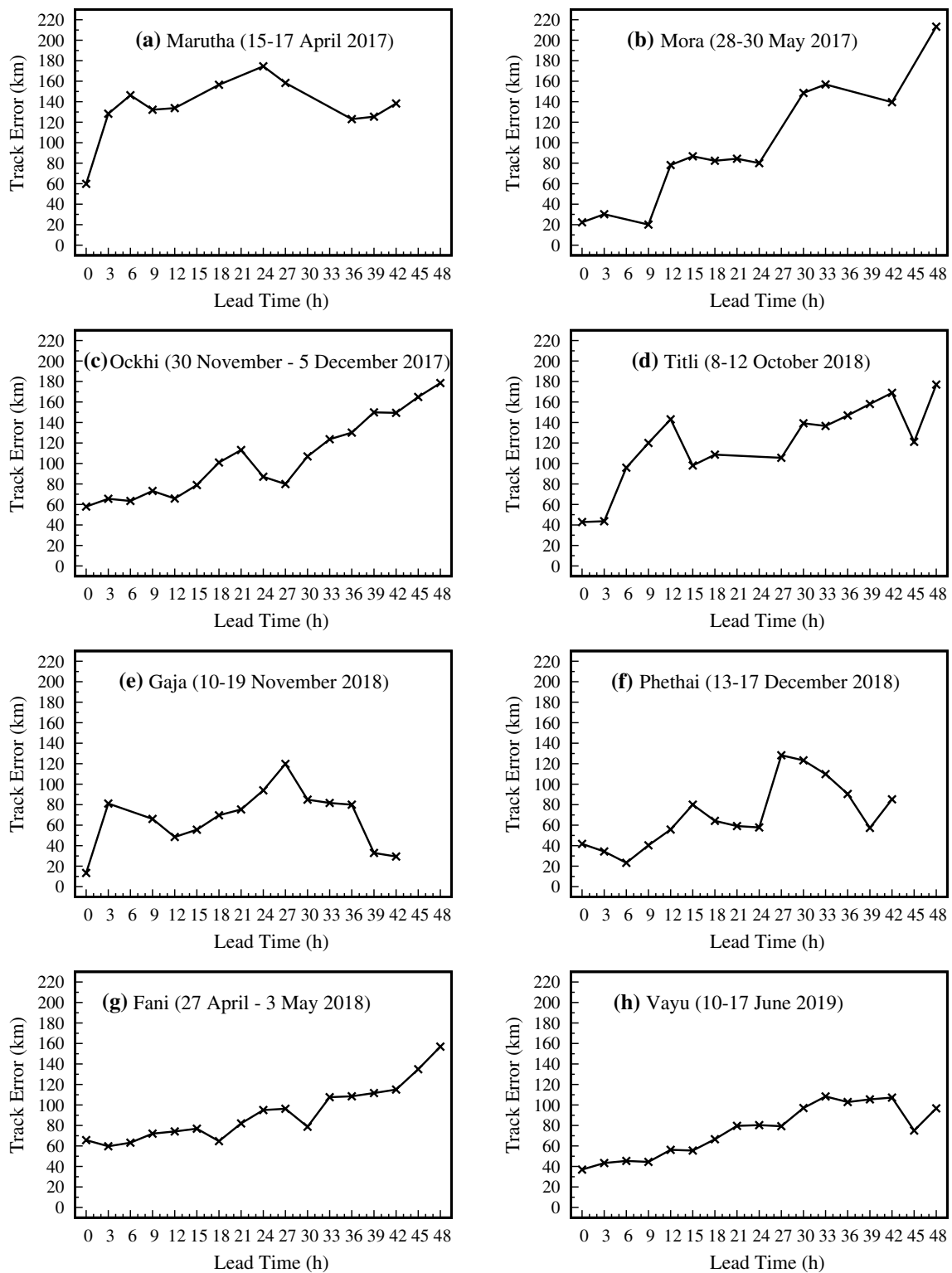
Fig. 2 Mean track error in the COSMO model-simulated cyclonic tracks (in km) for **a** Marutha, **b** Mora, **c** Ockhi, **d** Titli, **e** Gaja, **f** Phethai, **g** Fani, and **h** Vayu with respect to the observed track as a function of forecasting lead time
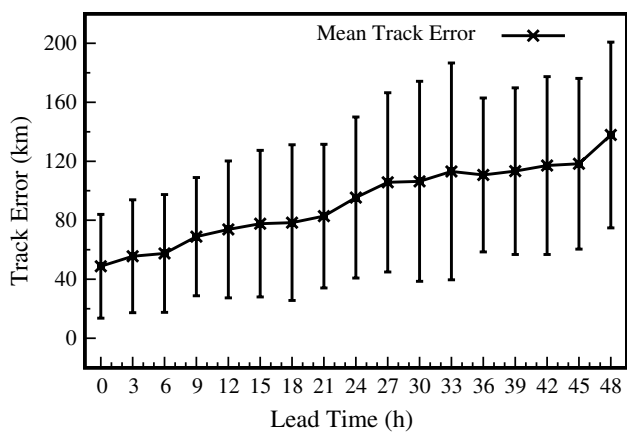
Fig. 3 Mean track error in the COSMO model-simulated cyclone tracks from the actual observed track obtained as a function of forecasting lead time during the study period of 2017–2019. Vertical bars indicate standard deviations corresponding to respective lead time

cyclone (Fig. 4a, b). We notice major differences between the simulated and observed pattern in $P_{Central}$, ΔP, and MSW, especially for the simulations with a lead time of 24–48 h (Fig. 4a–c). Such a difference is prominent in the case of Ockhi, Fani, and Vayu. Simulated values of the MSW for almost all the cyclones are comparatively larger than the concurrent observations (Fig. 4c). In one of the case studies dealing with the Ockhi cyclonic storm, Subrahamanyam et al. (2019) have attributed the errors in model simulations to the possible errors in the initial conditions of atmosphere provided to COSMO. In addition to the initial conditions provided to the regional NWP models, parametrized treatment of convection and ABL processes also play an important role in the intensity of the storm (Singh and Bhaskaran 2017).

A careful examination of the temporal variations in ΔP and MSW during the transition of a storm from low intensity to high intensity and vice versa indicate a probable change in the behaviour of model-simulated parameters for varying intensity of the storm. To investigate whether the COSMO model simulations behave differently for different stages of a storm, we have classified our database into four categories namely, the DD, CS, SCS, and VSCS. In Fig. 5, we present a composite picture of the simulated and observed intensity of the 8 TCs for these four categories. Three rows of Fig. 5a–c depict the differences between the model and observations for the pressure drop ($\delta \Delta P = \Delta P_{COSMO} - \Delta P_{IMD}$), MSW, and errors in the trajectory of cyclone as a function of the forecasting lead time. We have divided the forecasting lead time from 0 to 48 h into 8 equal time-bins of 6 h each, as depicted along the X axis in Fig. 5. The pressure drop simulated by COSMO for the DD and the CS stage is always larger in magnitude by 5–10 hPa than the concurrent observations (Fig. 5a). In contrast to this, the VSCS stage of

a cyclone is underestimated by the COSMO model for the first 24 h. An underestimation of the pressure drop also leads to low values of MSW which are also underestimated for the VSCS as well as SCS stage during the first 24 h of simulations (Fig. 5a, b). The model simulations with a lead time of more than 24 h yield a consistent overestimation of the pressure drop for all the stages of a cyclone. Broadly speaking, the track error associated with the COSMO predictions increases with increasing lead time (Fig. 5c). Another interesting observation is that the prediction of cyclone track is more accurate for the VSCS stage as against the DD stage. A combined assessment of the errors shown in three rows of Fig. 5a–c leads to the following points:

– COSMO model simulations with a lead time of 0–24 h yield better agreement with the concurrent observations as against those with a lead time of 24 h–48 h. In the present case, the departure of the model-simulated parameters from the observations with a lead time of more than 24 h can be attributed to the possible errors in LBCs. In one of the modelling studies with the aid of Weather Research and Forecasting (WRF), Singh and Bhaskaran (2018) have shown the impact of LBCs on the forecasted track and have attributed the errors in the model-simulated trajectory of a TC to the LBCs provided by the global models.

– During the initial stage of a cyclone, when its intensity is equal to that of a DD, COSMO overestimates the pressure drop irrespective of the forecasting lead time; however, the magnitudes of MSW are found to be close to the observations for the first 24 h. Beyond a lead time of 24 h, the MSW is roughly overestimated by 5 m s^{-1}. In conjunction with the errors in the pressure drop and the magnitudes of MSW, the exact location of the storm also remains uncertain during the DD stage of a cyclone.

– The predictability of the cyclone tracks for the VSCS stage is better than the remaining stages of the storm; however, the magnitudes of pressure drop and MSW are underestimated in this stage. This denotes that as soon as a storm attains severe intensity, the model can capture its location with better accuracy; however, the magnitude of the storm is underestimated for the first day's simulations. As the forecasting lead time goes beyond 24 h, the track prediction for the VSCS stage is still better than the other stages of a storm, but the intensity of the storm is overestimated, which can again be attributed to the LBCs.

For making a firm assessment on the predictability of TC trajectories for varying intensity through COSMO model, we have analyzed the error in model-simulated trajectories as a function of the simulated pressure drop (ΔP) through a scatter plot in Fig. 6. Standard thresholds

Fig. 4 COSMO model simulations together with the IMD observations of **a** central pressure ($P_{Central}$, in hPa); **b** pressure drop (ΔP, in hPa); and **c** maximum sustained surface wind speed (MSW, in m s^{-1}) for 8 TCs as a function of the Cyclone Day Number. Model simulations with a lead time of 0 to 24 h (first day) and 24–48 h (second day) are shown in different colours. Standard thresholds of the ΔP and MSW for classification of the TC as a Deep Depression (DD), Cyclonic Storm (CS), Severe Cyclonic Storm (SCS), and Very Severe Cyclonic Storm (VSCS) are marked as the horizontal lines in panel **b** and **c**
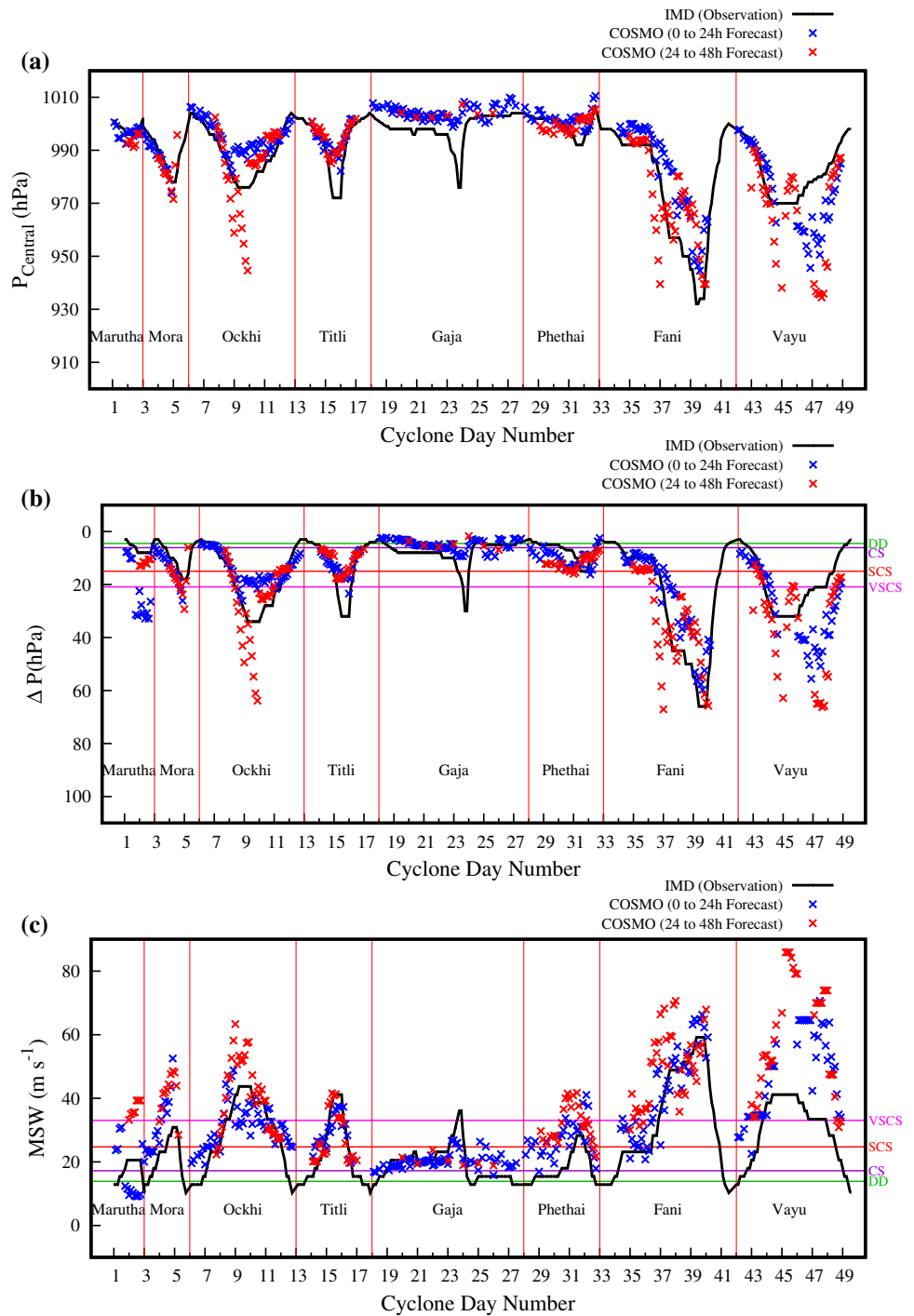
of ΔP for categorizing a storm into a DD, CS, SCS, VSCS, ESCS, and Super Cyclonic Storm (SuCS) are depicted by vertical lines along the ΔP-axis. During the initial stage of a TC, when the storm is categorized as a DD, we observe large variations in the track error. In other words, the uncertainty in the identification of the initial position of a TC is maximum for the DD stage, as the track error associated with this stage shows a variation from as low as 15 km to as large as about 140 km. As the intensity of the storm increases from a DD to CS, SCS, VSCS, and ESCS, the track error decreases with increasing magnitudes of ΔP. Such a decline in the track errors with increasing intensity of the storm indicates improved accuracy in the identification of the storm's position when it is well established.
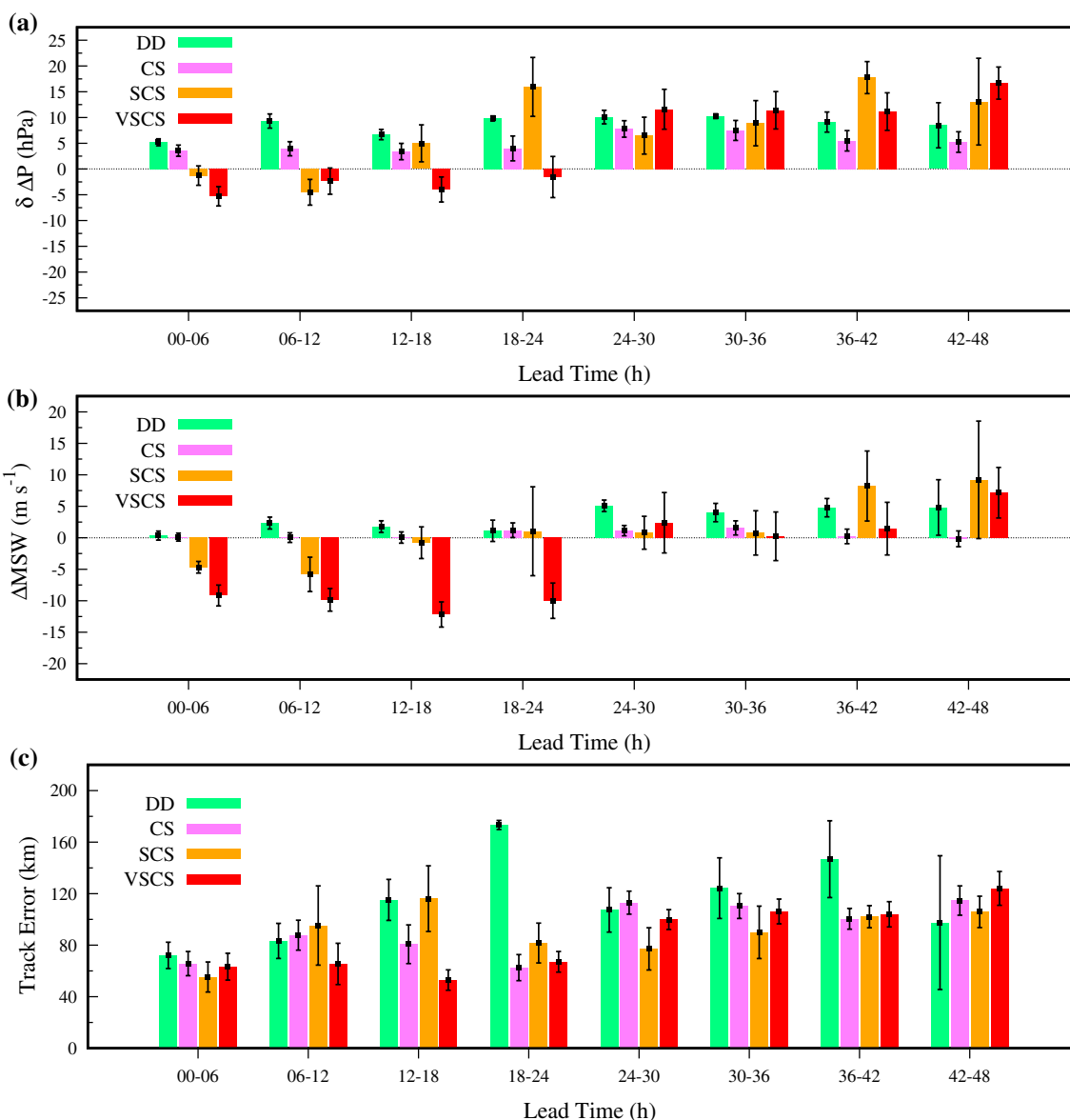
Fig. 5 Errors in the COSMO model simulations with respect to the IMD observations as a function of forecasting lead time. The lead time is divided into 8 time-bins of 6 h each along the X axis. **a** $\delta \Delta P$ (= ΔP_{COSMO} - $\Delta P_{IMD}$) in hPa; **b** ΔMSW (= MSW$_{COSMO}$ - MSW$_{IMD}$) in m s^{-1}; and **c** Error in the trajectory of TCs in km for different stages of the TC; namely, Deep Depression (DD), Cyclonic Storm (CS), Severe Cyclonic Storm (SCS), and Very Severe Cyclonic Storm (VSCS)

6 Conclusions

In this study, the performance of a regional NWP model COSMO is evaluated in prediction of the trajectories and intensities of 8 TCs over the BoB and the AS region. The model simulations of $P_{Central}$, ΔP, MSW, and the trajectories of these storms are validated against the observations obtained from e-Atlas of IMD. Furthermore, a special emphasis is paid on investigating the differential behaviour of COSMO model for four stages of a storm, i.e., DD, CS, SCS, and VSCS. Based on a comprehensive analysis of

these parameters for 8 TCs, we have derived the following conclusions:

1. The mean initial position error for 8 TCs was about 50 km. The predicted trajectories of these cyclones showed a dependence on the initial position error, whereas the differences of forecast cyclone tracks from analyzed ones with a lead time of more than 24 h we feel should be attributed primarily to errors in the LBCs.
2. Overall, there was a large amount of uncertainty in the identification of the eye of the storm for the low intensity
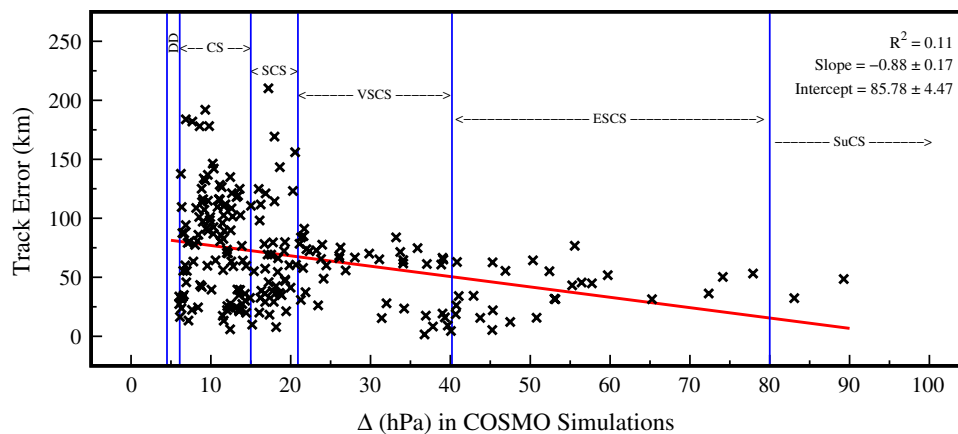
Fig. 6 Scatter plot of COSMO simulated pressure drop versus track error of tropical cyclones during the study period of 2017–2019. Red line is linear least square regression fits to data points. Categories of the storm based on pressure drop are also marked on the plot for quick referencing [Deep Depression (DD), Cyclonic Storm (CS), Severe Cyclonic Storm (SCS), Very Severe Cyclonic Storm (VSCS), Extremely Severe Cyclonic Storm (ESCS), and Super Cyclonic Storm (SuCS)]

of the storm, as the mean track error associated with the DD stage for all the lead times was 104 km, whereas it was about 80 km for the stage of VSCS.

3. For model simulations with a lead time of 0–24 h, the intensity of a storm in terms of ΔP is overestimated by COSMO for the DD stage, whereas the MSW variations for the DD as well as the CS stages are found to be in good agreement with the observations.

4. The errors in model-simulated trajectories are found to be dependent on the pressure drop. Low values of ΔP are often associated with large errors in the cyclone tracks, while high values of ΔP in COSMO model simulations yield relatively improved cyclone tracks.

5. A composite analysis of all the cyclones yields a mean track error of about 95 km for a lead time of 24 h, whereas it was about 140 km for the 48 h lead time.

Compliance with ethical standards

Conflicts of interest The authors declare that they have no conflict of interest.

References

Albert J, Bhaskaran PK (2020) Optimal grid resolution for the detection lead time of cyclogenesis in the north Indian Ocean. J Atmos Sol Terr Phys 204:105289. https://doi.org/10.1016/j.jastp.2020.105289

Anurose TJ, Subrahamanyam DB (2015) Evaluation of ABL parametrization schemes in the COSMO, a regional non-hydrostatic atmospheric model over an inhomogeneous environment. Model Earth Syst Environ 1:38. https://doi.org/10.1007/s40808-015-0045-y

Baldauf M, Seifert A, Förstner J, Majewski D, Raschendorfer M, Reinhardt T (2011) Operational convective-scale numerical weather prediction with the COSMO model: description and sensitivities. Mon Weather Rev 139(12):3887–3905. https://doi.org/10.1175/MWR-D-10-05013.1

Bhaskar Rao DV, Hari Prasad D, Srinivas D (2009) Impact of horizontal resolution and the advantages of the nested domains approach in the prediction of tropical cyclone intensification and movement. J Geophys Res Atmos 114:D11106. https://doi.org/10.1029/2008JD011623

Bhatla R, Raj R, Mall R, Shivani (2020) Tropical cyclones over the north Indian ocean in changing climate, vol 5. Wiley, Chap, pp 63–76. https://doi.org/10.1002/9781119359203.ch5

Chutia L, Pathak B, Parottil A, Bhuyan PK (2019) Impact of microphysics parameterizations and horizontal resolutions on simulation of "Mora" tropical cyclone over Bay of Bengal using numerical weather prediction model. Meteorol Atmos Phys 131:1483–1495. https://doi.org/10.1007/s00703-018-0651-0

Cruz FT, Narisma GT (2016) WRF simulation of the heavy rainfall over metropolitan Manila, Philippines during tropical cyclone Ketsana: a sensitivity study. Meteorol Atmos Phys 128:415–428. https://doi.org/10.1007/s00703-015-0425-x

Dube SK, Rao AD, Sinha PC, Murty TS, Bahulayan N (1997) Storm surge in the Bay of Bengal and Arabian Sea: the problem and its prediction. Mausam 48(1):283–304

Dube A, Ashrit R, Kumar S, Mamgain A (2020) Improvements in tropical cyclone forecasting through ensemble prediction system at NCMRWF in India. Tropical Cyclones Res Rev 9(2):106–116. https://doi.org/10.1016/j.tcrr.2020.04.003

Emanuel K (2003) Tropical cyclones. Ann Rev Earth Planetary Sci 31(1):75–104. https://doi.org/10.1146/annurev.earth.31.100901.141259

Fletcher RD (1955) Computation of maximum surface winds in hurricanes. Bull Am Meteorol Soc 36(6):247–250

Fotso-Kamga G, Fotso-Nguemo TC, Diallo I, Yepdo ZD, Pokam WM, Vondou DA, Lenouo A (2020) An evaluation of COSMO-CLM regional climate model in simulating precipitation over central Africa. Int J Clim 40(5):2891–2912. https://doi.org/10.1002/joc.6372

Ganesh S, Sahai A, Abhilash S, Joseph S, Dey A, Mandal R, Chattopadhyay R, Phani MK (2018) A new approach to improve the track prediction of tropical cyclones over north Indian Ocean. Geophys Res Lett 45(15):7781–7789. https://doi.org/10.1029/2018GL077650

IMD-RSMC Frequently asked questions (2021) Frequently asked questions on tropical cyclones. IMD, New Delhi. http://www.rsmcnewdelhi.imd.gov.in/images/pdf/cyclone-awareness/terminology/faq.pdf. Accssed: 14 January 2021

Jacobsen I, Heise E (1982) A new economic method for the computation of the surface temperature in numerical models. Beit Phy Atmos 55(2):128–141

Kumar P, Kishtawal CM, Pal PK (2015) Impact of ECMWF, NCEP, and ECMRWF global model analysis on the WRF model forecast over Indian region. Theor Appl Clim 127:143–151. https://doi.org/10.1007/s00704-015-1629-1

Kumar S, Lal P, Kumar A (2020) Turbulence of tropical cyclone "Fani" in the Bay of Bengal and Indian subcontinent. Nat Hazards 103:1613–1622. https://doi.org/10.1007/s11069-020-04033-5

Kurowski MJ, Wojcik DK, Ziemianski MZ, Rosa B, Piotrowski ZP (2016) Convection-permitting regional weather modeling with COSMO-EULAG: compressible and anelastic solutions for a typical westerly flow over the Alps. Mon Weather Rev 144(5):1961–1982. https://doi.org/10.1175/MWR-D-15-0264.1

Langmack H, Fraedrich K, Sielmann F (2012) Tropical cyclone track analog ensemble forecasting in the extended Australian basin: NWP combinations. Q J R Meteorol Soc 138(668):1828–1838. https://doi.org/10.1002/qj.1915

Mesinger F, Veljovic K (2020) Topography in weather and climate models: Lessons from cut-cell Eta vs. European Centre for Medium-Range Weather Forecasts experiments. J Meteorol Soc Japan Ser II 98(5):881–900. https://doi.org/10.2151/jmsj.2020-050

Mishra SP, Sethi KC, Mishra DP, Siddique M (2019) Pre-monsoon cyclogenesis over Bay of Bengal. Int J Recent Tec Engg 8(2):4895–4908. https://doi.org/10.35940/ijrte.B3694.078219

Mohanty UC, Gupta A (1997) Deterministic methods for prediction of tropical cyclone tracks. Mausam 2:252–272

Mohanty S, Nadimpalli R, Mohanty UC, Mohapatra M, Sharma A, Das AK, Sil S (2020) Quasi-operational forecast guidance of extremely severe cyclonic storm Fani over the Bay of Bengal using high-resolution mesoscale models. Meteorol Atmos Phys. https://doi.org/10.1007/s00703-020-00751-4

Mohapatra M, Bandyopadhyay B, Tyagi A (2011) Best track parameters of tropical cyclones over the north Indian Ocean: a review. Nat Hazards 63:1285–1317. https://doi.org/10.1007/s11069-011-9935-0

Mohapatra M, Nayak DP, Bandyopadhyay BK (2012) Evaluation of cone of uncertainty in tropical cyclone track forecast over north Indian ocean issued by India Meteorological Department. Tropical Cyclones Res Rev 1(3):331–339. https://doi.org/10.6057/2012TCRR03.02

Mohapatra M, Nayak DP, Sharma RP, Bandyopadhyay BK (2013) Evaluation of official tropical cyclone track forecast over north Indian ocean issued by India Meteorological Department. J Earth Syst Sci 122(3):589–601. https://doi.org/10.1007/s12040-013-0291-1

Mukhopadhyay P, Taraphdar S, Goswami B (2011) Influence of moist processes on track and intensity forecast of cyclones over the north Indian ocean. J Geophy Res Atmos 116:D05116. https://doi.org/10.1029/2010JD014700

Murav'ev A, Kiktev D, Bundel' A, Dmitrieva T, Smirnov A (2015) Verification of high-impact weather event forecasts for the region of the sochi-2014 olympic games. part I: Deterministic forecasts during the test period. Russ Meteorol Hydrol 40:584–597. https://doi.org/10.3103/S1068373915090034

Nadimpalli R, Srivastava A, Prasad VS, Osuri KK, Das AK, Mohanty UC, Niyogi D (2020) Impact of INSAT-3D/3DR radiance data assimilation in predicting tropical cyclone Titli over the Bay of Bengal. IEEE Trans Geosci Remote Sens 58(10):6945–6957. https://doi.org/10.1109/TGRS.2020.2978211

Osuri KK, Mohanty UC, Routray A, Mohapatra M, Niyogi D (2013) Real-time track prediction of tropical cyclones over the north Indian ocean using the ARW model. J Appl Meteorol Clim 52(11):2476–2492. https://doi.org/10.1175/JAMC-D-12-0313.1

Ritter B, Geleyn JF (1992) A comprehensive radiation scheme for numerical weather prediction models with potential applications in climate simulations. Mon Weather Rev 120(2):303–325. https://doi.org/10.1175/1520-0493(1992)120$<$0303:ACRSFN$>$2.0.CO;2

Roshny S, Subrahamanyam DB, Anurose TJ, Ramachandran R (2018) Impact analysis of dynamical downscaling on the treatment of convection in a regional NWP model - COSMO: a case study during the passage of a very severe cyclonic storm "Ockhi". Nat Haz Earth Syst Sci Disc 2018:1–26. https://doi.org/10.5194/nhess-2018-288

Samiksha V, Vethamony P, Antony C, Bhaskaran P, Nair B (2017) Wave-current interaction during Hudhud cyclone in the Bay of Bengal. Nat Haz Earth Syst Sci 17:2059–2074. https://doi.org/10.5194/nhess-17-2059-2017

Schättler U, Doms G, Schraff C (2018) A description of the nonhydrostatic regional COSMO-Model. DWD Report: User's Guide COSMO V5.05:175 pp

Sharma SK, Misra SK, Singh JB (2020) The role of GIS-enabled mobile applications in disaster management: a case analysis of cyclone Gaja in India. Int J Info Manag 51:102030. https://doi.org/10.1016/j.ijinfomgt.2019.10.015

Shrestha P, Dimri AP, Schomburg A, Simmer C (2015) Improved understanding of an extreme rainfall event at the Himalayan foothills: a case study using COSMO. Tellus A Dyn Meteorol Ocean 67(1):26031. https://doi.org/10.3402/tellusa.v67.26031

Singh K, Bhaskaran PK (2017) Impact of PBL and convection parameterization schemes for prediction of severe land-falling Bay of Bengal cyclones using WRF-ARW model. J Atmos Sol Terr Phys 165–166:10–24. https://doi.org/10.1016/j.jastp.2017.11.004

Singh K, Bhaskaran PK (2018) Impact of lateral boundary and initial conditions in the prediction of Bay of Bengal cyclones using WRF model and its 3D-VAR data assimilation system. J Atmos Sol Terr Phys 175:64–75. https://doi.org/10.1016/j.jastp.2018.05.007

Singh R, Kishtawal C, Pal P, Joshi P (2012) Improved tropical cyclone forecasts over north Indian ocean with direct assimilation of AMSU-A radiances. Meteorol Atmos Phys 115:15–34. https://doi.org/10.1007/s00703-011-0165-5

Subrahamanyam DB, Ramachandran R, Nalini K, Paul FP, Roshny S (2019) Performance evaluation of COSMO numerical weather prediction model in prediction of Ockhi—one of the rarest very severe cyclonic storms over the Arabian sea: a case study. Nat Hazards 96:431–459. https://doi.org/10.1007/s11069-018-3550-2

Subrahamanyam DB, Roshny S, Paul FP, Anurose TJ, Ramachandran R (2020) Impact of a very severe cyclonic storm "Ockhi" on the vertical structure of marine atmospheric boundary layer over the Arabian Sea. Bull Atmos Sci Tech. https://doi.org/10.1007/s42865-020-00020-7

Tang BH, Fang J, Bentley A, Kilroy G, Nakano M, Park MS, Rajasree VPM, Wang Z, Wing AA, Wu L (2020) Recent advances in research on tropical cyclogenesis. Tropical Cyclones Res Rev 9:87–105. https://doi.org/10.1016/j.tcrr.2020.04.004

Tiedtke M (1989) A comprehensive mass flux scheme for cumulus parameterization in large-scale models. Mon Weather Rev 117(8):1779–1800. https://doi.org/10.1175/1520-0493(1989)117$<$1779:ACMFSF$>$2.0.CO;2

Zängl G, Reinert D, Rípodas P, Baldauf M (2015) The icon (icosahedral non-hydrostatic) modelling framework of DWD and MPI-M: description of the non-hydrostatic dynamical core. Q J R Meteorol Soc 141(687):563–579. https://doi.org/10.1002/qj.2378

Zhou R, Gao W, Zhang B, Chen Q, Liang Y, Yao D, Han L, Liao X, Li R (2017) A new prediction model of daily weather elements in hainan province under the typhoon weather. Meteorol Atmos Phys 131:1–20. https://doi.org/10.1007/s00703-017-0567-0

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.