ORIGINAL ARTICLE

Role of PBL and air-sea flux parameterization schemes in the forecast of super cyclone Amphan and ESCS Phailin in the cloud-resolving scale using WRF-ARW model

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Abstract

The present study evaluates the role of turbulence mixing in the boundary layer and surface roughness schemes through parameterization of the planetary boundary layer (PBL) and air-sea flux (ASF) schemes, respectively, in the prediction of Super Cyclonic Storm (SuCS) Amphan 2020 and Extremely Severe Cyclonic Storm (ESCS) Phailin 2013 over the Bay of Bengal region. This study utilized a high-resolution Advanced Research version WRF (WRF-ARW) modelling system with a moving-nested domain in a cloud-resolving scale about 1.667 km horizontal resolution. Six simulations were conducted with two PBL (YSU non-local and MYJ local) schemes and three air-sea flux (FLUX0, FLUX1, and FLUX2) schemes. In the last the time-varying Sea Surface Temperature (SST) was also updated for those simulations having over-predictions in the maximum surface wind (MSW). The model predicted track, intensity, and structures were validated with the Indian Meteorological Department best-fit track data, Doppler Weather Radar (DWR), and Cooperative Institute for Research on Atmosphere (CIRA) multiplatform satellite datasets. Results suggested that model simulations provided a better forecast in MSW using the MYJ-FLUX2 experiment with mean absolute errors of about 5.3 m/s, followed by the MYJ-FLUX1 experiment. The simulated rapid intensification in both cases (Amphan and Phailin) was well captured in the MYJ-FLUX1 and MYJ-FLUX2 experiments. The time-varying SST experiments provided less intensity compared to without SST experiments and showed a positive impact on the forecast of MSW in the first two days with the YSU-FLUX1 experiment. For a better understanding about under-prediction and over-prediction during the entire simulation period were presented and discussed in terms of microphysics latent heating, and divergence. Storm structures in terms of spatial wind speed and vertical structure of temperature anomaly suggested that simulations were varying by changing PBL and ASF schemes. Overall, the YSU-FLUX1 experiment showed a better prediction in terms of track of the storms, with a mean track error of about 63 km. This study suggested that the high horizontal resolution about 1.667 km using YSU-FLUX1 with SST in the WRF model provided a better representation of the intensity and storm structures of ESCS Phailin and SuCS Amphan.

Keywords PBL · Air-sea flux · Moving-nest · Bay of Bengal · Intensity and structure

Introduction

In the North Indian Ocean, the Bay of Bengal (BoB) region is considered a high-risk basin associated with land-falling tropical cyclones(Das et al. 2016; Sahoo and Bhaskaran 2016; Deshpande et al. 2021). The intensity, lifetime, and duration of extremely severe cyclonic storms (ESCS; maximum surface wind speed greater than 90 knots) have increased (Singh et al. 2022). Hence, an accurate forecast of these land-falling storms over the BoB using the Numerical Weather Prediction (NWP) model is necessary and will

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assist in minimizing damages and facilities nearer to the coast. In the last two decades, high-resolution NWP models have been more successful in predicting TCs due to recent advancements in computational power, improved representation of physical processes (Verma et al. 2021; Nekkali et al. 2022), the use of the more accurate technique of data assimilation (Kalra et al. 2019; Thodsan et al. 2021; Gogoi et al. 2022; Tiwari et al. 2022), high horizontal model resolution(Hossain et al. 2022; Moon et al. 2021; Xu and Wang 2021), increased network of observation, coupling with ocean models (Zi-Qian and An-Min 2012; Lok et al. 2022). The tropical cyclone track forecast has shown significant improvement (Wu et al. 2010, 2016; Mohapatra et al. 2013; Lengaigne et al. 2019; Moon et al. 2021). However, there are still limitations in accurately predicting the intensity of cyclones (Emanuel et al. 2016; Roy et al. 2024). This is primarily due to the complex interaction between inner core dynamics, physical processes, storm structure, and rapid intensification, which remains a current research topic. A high-resolution modeling system is important for forecasting inner core structures and for better representations of physical processes in the eyewall(Chen et al. 2007; Davis et al. 2008). Furthermore, to understand the small-scale dynamics, a higher horizontal resolution is crucial (Park et al. 2020). Therefore, the current study expected that a high-resolution (less than 2 km) modeling system would provide a better forecast of intensity and inner-core storm structures.

The reliability and selection of physics parametrization (convection, boundary layer, microphysics, air-sea interaction, and land surface) schemes in the NWP models over a particular region are essential and have an effect on the prediction of track, intensity, and inner core structures of the storms. Numerous studies have shown that planetary boundary layer (PBL) schemes significantly affect the track, intensity, and structure forecast of tropical storms (Kanada et al. 2012; Gopalakrishnan et al. 2013; Vijaya Kumari et al. 2019; Njuki et al. 2022). A study by Rajeswari et al. (2020) showed that the PBL schemes determine energy flow in the air-sea interface and throughout the atmosphere and hence play a vital role in the prediction of TCs. The PBL scheme helps regulate surface fluxes of momentum, latent heat, and sensible heat, which are essential in the formation and development of tropical cyclones(Das et al. 2015) and PBL schemes have a crucial role in the intensification of the storm (Pattanayak et al. 2012). A study by Verma et al. (2021) suggested that the nonlocal YSU and local MYJ PBL are more accurate in forecasting cyclone intensity, tracks, and rainfall over the NIO. Other studies also demonstrated TC forecasts over the BoB region using the YSU PBL scheme, suggesting better storm forecasting. Still, these studies were based on a low resolution of more than 5 km (Kanase and Salvekar

2015). Studies (Kueh et al. 2019; Yesubabu et al. 2020; Kattamanchi et al. 2021; Rizza et al. 2021; Ye et al. 2022) suggested that parameterizing the air-sea flux in NWP models improved the TCs forecast regarding intensity, structure, and track. Air-sea flux processes significantly influence the initiation and growth of TCs through energy in the form of moisture and heat exchanges (Greeshma et al. 2019). Furthermore, a study by Singh et al. (2023) revealed that the track, landfall, and intensity forecast were improved using the YSU PBL scheme with the enthalpy coefficient for heat and moisture air-sea flux scheme in a 3 km horizontal resolution of the WRF model.Tang et al. (2018) suggested that an advanced regional modeling system with a grid spacing of less than 2 km better represents the small-scale physical processes in the boundary layer and is also important for model development in the eyewall region.Mohanty et al. (2019) suggested that updating the real time SST in Hurricane WRF at 9 km horizontal resolution provided a better forecast of the storms in terms of intensity, rainfall, and track.

A study by Zhu and Zhang (2006) shows that the track is found to be unresponsive to the storm-induced SST cooling, but the hurricane intensity is highly sensitive. SST plays a critical role in the air-sea interaction of TC dynamics and intensity (Zhang et al. 2021; Li and Chen 2022). The latent and sensible heat fluxes influenced by SST play a crucial role in TC processes (Li and Chen 2022). Hence it is expected that to test the model performance in the forecast of intensity and inner core structures of the storms by using these two best-performing PBL (YSU and MYJ) schemes and available air-sea flux parameterization schemes with and without varying SST in the cloud-resolving scale (less than 2 km horizontal resolution) over the BoB region.

The present study was conducted with two rapidly intensified TCs over the Bay of Bengal, namely Super Cyclonic Storm (SuCS) Amphan 2020 (Vissa et al. 2021; Chatterjee and Roy 2021; Nahar et al. 2022; Ahmed et al. 2021) and Extremely Severe Cyclonic Storm (ESCS) Phailin 2013 (Mittal et al. 2019; Mandal et al. 2016; Pradhan et al. 2021). Little research has been done on the simultaneous study of the impact of PBL, air-sea interaction, and SST influence using the WRF model on a cloud-resolving scale (less than 2 km horizontal resolution). This study aims to analyse the impact of PBL and air-sea flux schemes using a high horizontal resolution (1.667 km) WRF-ARW model. The framework of this paper is as follows: Sect. 2 covers the Methodology used in the study. Section 3 covers the result analysed using finer domain simulations, in which results will cover the impact of PBL and air-sea flux parameterization schemes in the forecast of the structure, intensity, and track of two intense TCs. Finally, Sect. 4 deals with the conclusions of the study.

Methodology

Model framework

A three-dimensional non-hydrostatic Advanced Research version of the Weather Research and Forecasting (WRF-ARW) atmospheric model of version 4.0 was used in this study (Skamarock et al. 2019). The mesoscale modelling system WRF-ARW is developed by the National Oceanic and Atmospheric Administration (NOAA), the National Center for Environmental Prediction (NCEP), and several universities collaborated with the National Center for Atmospheric Research (NCAR) (Raju et al. 2011). The model implements an Arakawa C-type horizontal grid and a terrain-following hydrostatic pressure vertical coordinate (Rajeswari et al. 2020). The model makes use of second to sixth-order advection methods in both vertical and horizontal directions, along with the Runge-Kutta second and third-order time integration schemes. It also includes a variety of physics schemes and data-assimilation packages. Recently several studies (Kutty et al. 2020; Vishwakarma et al. 2021; Huang et al. 2022; Verma et al. 2023) used the WRF-ARW modelling system for the prediction of tropical cyclones.

The present study used three two-way interactive nested domains D1, D2, and D3 with a horizontal resolution of 15 km, 5 km, and 1.667 km, respectively, where D2 and D3 were considered on a moving nested platform (Chen et al. 2018; Liao et al. 2022; Singh et al. 2023). The outer domain (D1) comprises 232×265 grid points; the second domain (D2) comprises 193×193 grid points; and the finer domain (D3) comprises 403×403 grid points. The model domain is presented in Fig. 1. The model integration time step size was considered to be about 75s, 25s, and 8.333s for the domain D1 to D3, including 51 vertical levels. Inner domains (D2 and D3) were explicitly resolved with the cumulus convection scheme and hence switched off the cumulus convection from the domains D2 and D3. The parameterization schemes used for the numerical experiments are the Lin scheme (Lin et al. 1983) for microphysics, the Non-local diffusion Yonsei University (YSU) scheme (Hong et al. 2006), and the MYJ local diffusion scheme (Janjic et al. 1994) for the PBL, Kain-Fritsch (Kain 2004) scheme for cumulus convection, Rapid Radiative Transfer Model (RRTM; Mlawer et al. 1997) for long-wave radiation, Dudhia (Dudhia 1989) scheme for short-wave radiation, and Noah land surface model (Noah LSM; Ek et al. 2003). In the study with and without enthalpy coefficients (isftcflx = 0, 1, and 2) were also utilized to test the cyclone forecast over the Bay of Bengal region.

Data

The model initial condition and boundary conditions for numerical simulations are derived from NCEP FNL analysis
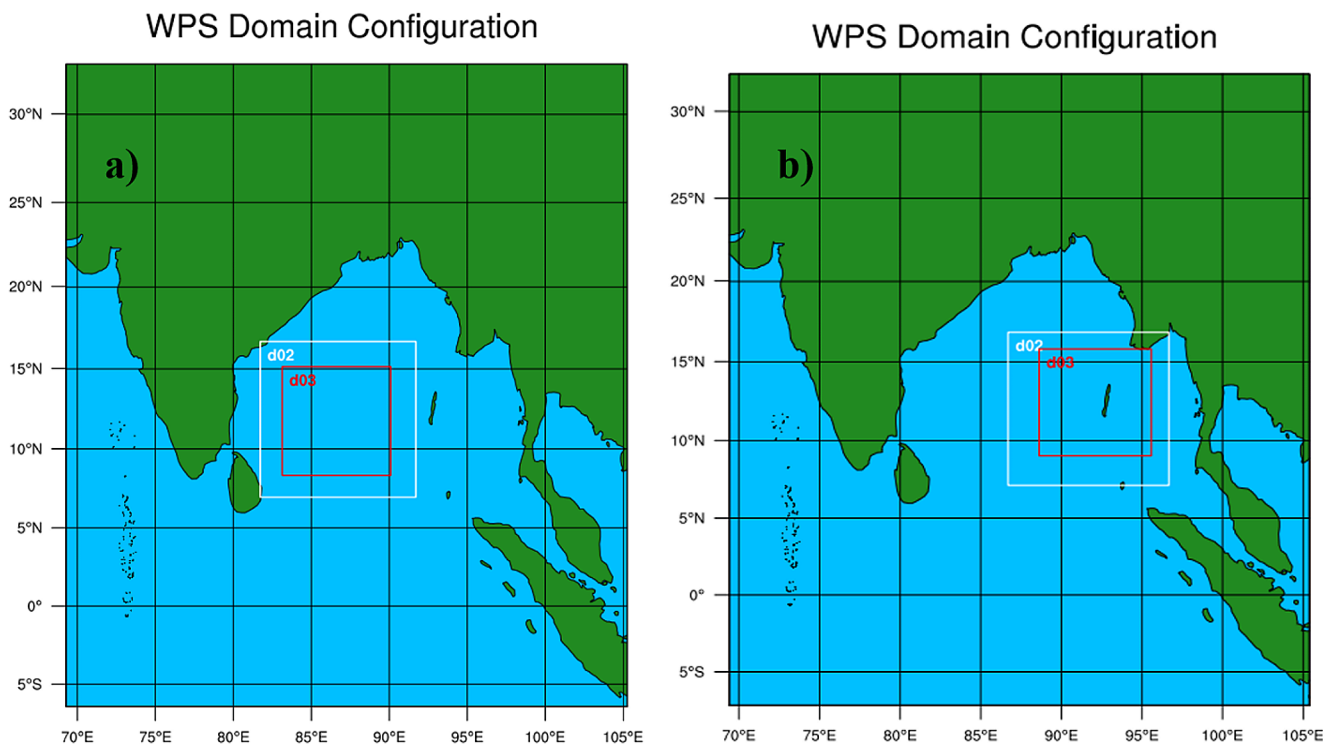

Fig. 1 Triple nested model domains with resolutions of 15 km (d01), 5 km (d02), and 1.667 km (d03) for **a**) SuCS Amphan, and **b**) ESCS Phailin in which domains d02 and d03 are considered to be moving nested

datasets available at every six-hour interval with a horizontal resolution of about 1°x1° (https://rda.ucar.edu/datasets/ds083.2/). The temporal lateral boundary conditions are given at every six hours for model integration. The model simulated finer domain (D3) results such as track, intensity in terms of minimum sea level pressure (MSLP), and maximum surface wind (MSW) of the storms were validated with available best-fit track observations from the India Meteorological Department (IMD) and Cooperative Institute for Research on Atmosphere (CIRA) multiplatform satellite data for temperature anomalies and wind speed and the simulated storm structures were also compared with available Doppler Weather Radar (DWR) observations, and satellite observations to validate the model results (Knaff et al. 2011; Nellipudi et al. 2021). For SST initialization, the data was derived from the fifth generation of the European Centre for Medium-Range Weather Forecasts (ECMWF), considered as ERA5 reanalysis at every 6-hour interval with a horizontal resolution of 0.25° x 0.25° (https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels).

Numerical experiments

In the study, a total of 12 experiments were conducted using a combination of two PBL schemes (YSU, MYJ) and three air-sea flux (ASF; isftcflx = 0, 1, and 2) parameterization schemes. For ASF where option 0 (referred as FLUX0) is followed by the Garrett surface drag C_D and moist enthalpy C_k (monotonic increases in surface drag with wind speed), option 1 (referred as FLUX1) is Donelan C_D + Constant C_k (C_D is associated with high wind speed), and option 2 (referred as FLUX2) is Donelan C_D + Garrett C_k (C_D is associated with high wind speed) (Powell et al. 2003; Donelan et al. 2004; Nellipudi et al. 2021) on two different intense TCs, namely super cyclone Amphan and extremely severe cyclonic storm Phailin. The model was initialized for ESCS Phailin and SuCS Amphan at the cyclonic stage at 12 UTC on 09 October 2013, and 00 UTC on 17 May 2020 respectively with the forecast lengths of 4 days. However, finer domain (D3) results were used to validate with available observations. Table 1 provides more details about the

Table 1 Details about numerical experiments considered in the study

Six experiments between two PBLs (YSU & MYJ) and three air-sea flux schemes (FLUX0, FLUX1 & FLUX2)	1. YSU-FLUX0 2. YSU-FLUX1 3. YSU-FLUX2 4. MYJ-FLUX0 5. MYJ-FLUX1 6. MYJ-FLUX2

experiments. In addition, four more experiments were conducted using time varying Sea Surface Temperature (SST) based on the above experiments, which provided an overestimation in MSW.

Track error was computed by measuring the distance between the predicted and observed positions of the cyclone at a specific time, mean error and absolute errors of track and intensity were calculated using the following formulas:

$$Track\ error\,(in\ km) = \sqrt{(\Delta lat)^2 + (\Delta lon)^2} * 111 \tag{1}$$

$$Absolute\ Error = |O_i - P_i| \tag{2}$$

$$Mean\ Error = \frac{\sum (Errors)}{n} \tag{3}$$

All errors are considered at a specific time between Observations (O_i) and model predicted (P_i) and n is the number of observations at every three-hour interval.

Temperature Anomaly (T_{anom}) was assessed by subtracting the temperature at a particular time (T_t) and mean temperature (T_{mean}) obtained from the 96-hour forecast period using domain 1 results. The T_{anom} was calculated using following formula

$$T_{anom} = T_t - T_{mean} \tag{4}$$

Results and discussion

The study evaluated the performance of WRF-ARW model in forecast of SuCS Amphan and ESCS Phailin cyclone in a cloud resolving scale with high horizontal resolution about 1.667 km to see the influence of PBL and air-sea flux parametrization schemes. The results were presented in terms of intensity [Minimum Sea Level Pressure (MSLP) and Maximum Surface Wind (MSW)], rapid intensification (RI: wind changes in 24-hour intervals with wind speed greater than 15.4 m/s), are analysed in Sect. 3.1. The forecast of structure in terms of microphysics latent heating, divergence, reflectivity, temperature anomaly, and wind speed is discussed in the Sect. 3.2. The forecasted track obtained from six experiments is compared with the IMD best-fit track data included in Sect. 3.3. Moreover, Sect. 3.4 covers the role of sea surface temperature (SST) in the forecast of intensity of the storms using YSU-FLUX1 and YSU-FLUX2 experiments, since these experiments provided an over-estimation during entire simulation period.

Impact on intensity forecast

The intensity of SuCS Amphan and ESCS Phailin in terms of MSW and MSLP obtained from six experiments along with the IMD best-fit track is revealed in Fig. 2. It is significant to highlight that in the analysis, observations and models results were presented using 3-hour intervals and first 6 h results considered as spin-up time and hence not considered in the analysis. The Fig. 2 demonstrates that the initial 36 h of the forecast displayed a consistent pattern in the forecast of MSW of Amphan cyclone, except for YSU-FLUX1 experiment, followed by YSU-FLUX2 experiment. It was observed that, there was a slight change in both cases Amphan and Phailin during the intensification phase. The intensity pattern in terms of both MSW and MSLP depicts that YSU-FLUX1, followed by YSU-FLUX0, and YSU-FLUX2, depict an overestimation during the intensification phase, which extended roughly during 30 h to 72 h forecast period. This was followed by a consistent trend that continued until the dissipation stage. Similar to the study by Rajeswari et al. (2020), both Amphan and Phailin model simulations showed an overestimation in the MSLP compared to observation, during the intensification phase. Results from Amphan cyclone, the MSW pattern from MYJ-FLUX1 and MYJ-FLUX2 is closer to observation, with the least MSW error at 4.6 m/s and 4.3 m/s, respectively. Meanwhile, there are slight variations in the MSLP patterns in the experiments with MYJ-FLUX1 and MYJ-FLUX2, with a mean error of roughly 14 hPa and 13 hPa, respectively. In case of Phailin the MSW pattern varies noticeably during the intensification stage in each model experiment. The MSW and MSLP patterns show more significant variations for YSU-FLUX1 experiment, which is especially notable.

During the intensification phase, it reaches a peak intensity of about 73.6 m/s and 901 hPa. Whereas, the maximum observed intensity for the Phailin that time was recorded about 59.1 m/s for MSW and 940 hPa for MSLP. It is observed that, in comparison to the other schemes, YSU-FLUX1 continuously overestimated the intensity forecast in terms of MSW and MSLP during the intensification period suggesting more effective reproduced cyclones. Hence, YSU-FLUX1 showed a higher intensity error for MSW and MSLP of with mean errors about 7 m/s and 15 hPa, respectively for Phailin cyclone.

Overall, the mean MSW error of six experiments YSU-FLUX1, YSU-FLUX2, MYJ-FLUX1, MYJ-FLUX2, YSU-FLUX0, and MYJ-FLUX0 is 9.37 m/s, 6.4 m/s, 5.3 m/s, 5.27 m/s, 6.9 m/s, and 6.0 m/s, respectively (Table 2). Which indicated that MYJ-FLUX2 and MYJ-FLUX1 experiments produced better forecast of MSW results with least error. With MSLP mean error is about 19 hPa, 8.8 hPa, 11.74 hPa, 11.4 hPa, 10.5 hPa, and 11.78 hPa, respectively. The results showed that the PBL schemes and air-sea flux parametrization schemes in the high-resolution WRF-ARW model significantly influence the intensity. This is particularly relevant during the intensification phase for the ESCS Phailin and SuCS Amphan.

The model-simulated 24-hour wind changes along with IMD best-fit track data for both cases are depicted in Fig. 3. The rapid intensification (24-hour wind speed changes greater than 15.4 m/s) and dissipation pattern (24-hour wind speed changes less than −15.4 m/s) derived from model experiments demonstrate that the model is capable of predicting patterns with small variations in both cases when utilizing the high-resolution modelling system. In the Amphan case, the YSU-FLUX1 simulation shows an
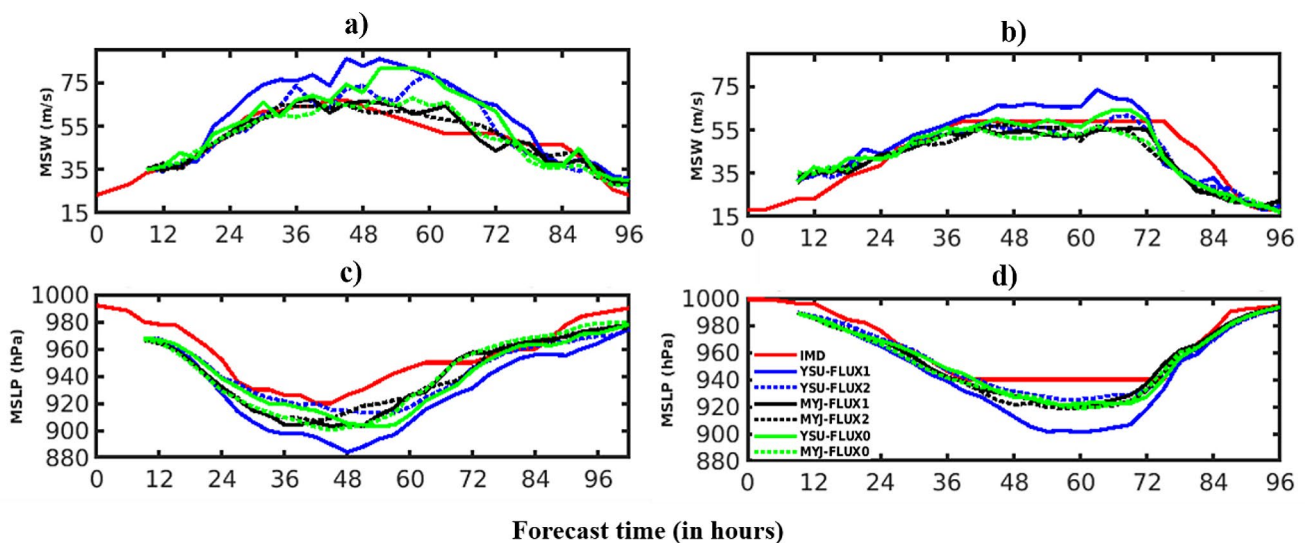

Fig. 2 Time variation of model simulated maximum surface wind (MSW, in m/s) and minimum sea level pressure (MSLP, in hPa) along with IMD best-fit track data (**a & c**) for SuCS Amphan and (**b & d**) for ESCS Phailin, respectively

Table 2 The model simulated daily basis errors and mean errors using 3 hourly datasets for the track (in km), MSW (in m/s), and MSLP (in hPa) from different experiments

Model simulated track and intensity errors					
	Day-1	Day-2	Day-3	Day-4	Mean Error
Track error (in km)					
YSU-FLUX0	46	23	63	150	64
YSU-FLUX1	**40**	**38**	**64**	**125**	**63**
YSU-FLUX2	43	31	66	157	65
MYJ-FLUX0	44	44	80	173	74
MYJ-FLUX1	39	32	95	186	78
MYJ-FLUX2	37	36	91	175	75
MSW error (in m/s)					
YSU-FLUX0	3.2	3.6	0.57	1.9	6.9
YSU-FLUX1	7.4	12.6	6.0	3.8	9.4
YSU-FLUX2	1.5	6.7	3.2	4.0	6.4
MYJ-FLUX0	1.5	4.3	5.5	4.0	6.0
MYJ-FLUX1	**2.1**	**3.8**	**3.8**	**2.0**	**5.3**
MYJ-FLUX2	**2.4**	**2**	**7.3**	**9**	**5.3**
MSLP error (in hPa)					
YSU-FLUX0	10.6	16.9	7.4	7.1	10.5
YSU-FLUX1	18	34.7	17.5	9	19.1
YSU-FLUX2	9.6	10.2	5.2	10	8.8
MYJ-FLUX0	16.6	17.6	6.8	4.6	11.8
MYJ-FLUX1	15.4	17.1	3.5	6	11.7
MYJ-FLUX2	14.8	15.7	5	6.8	11.4

overestimation of about 14 m/s after 24 to 48 h of simulation time. The model then accurately reflected the ESCS stage and displayed some variation in the deepening stage. The Phailin analysis reveals that all simulations accurately represented the pattern, except YSU-FLUX1, which exhibits underestimation in the rapid dissipation stage. Finally, the above results suggest that the YSU-FLUX1 experiment shows an overestimation in intensity. The model-predicted results showed that both MYJ-FLUX1 and MYJ-FLUX2 experiments better captured the observation pattern. Overall, results suggested that modelling system is able to capture

the pattern and magnitude of the RI in both cases with better accuracy with MYJ PBL scheme.

Impact on structure forecast

The model predicted microphysics latent heating (in shaded), and divergence (in contour) which were analysed to see the impact of these parameters in forecast of intensity of the storms and intensification and dissipation pattern. For this the time variation of the simulated microphysics latent heating and divergence of SuCS Amphan is depicted in Fig. 4a, and that of Phailin is depicted in Fig. 4b, by taking the area average across the moving domain DO3 (1.667 km resolution). The results from Amphan cyclone (Fig. 4a), the distribution pattern of microphysics latent heating and divergence in the first 48 h (00 UTC May 17 to 00 UTC May 19) exhibits a higher distribution and subsequently represents the dissipation stage and which matched with intensity of the storm. All the experiments for Amphan cyclone show the three peaks of latent heating from 5 to 10 km, and the higher upper-level divergence from 5 km to about 17 km height well matches the MSW (Fig. 2). Likewise, the intensification and dissipation of ESCS Phalin are significantly influenced by the middle-upper-level divergence between 5 and 16 km and the latent heating pattern between 5 and 10 km (Fig. 4b).

The model forecast skill in simulating both storm structures are also discussed based on the combinations of PBL and air-sea flux parameterization schemes in terms of the structure of maximum reflectivity, temperature anomaly, and wind speed. The model predicted maximum reflectivity at about 0900 UTC on 19 May 2020 for SuCS Amphan along with the Visakhapatnam DWR image, are depicted in Fig. 5. The observation pattern of Amphan depicts a thick cloud pattern present between 16°N and 18°N and also well-resolved cloud bands between 19°N and 20°N over the land. The result signifies that all YSU experiments (YSU-FLUX0,
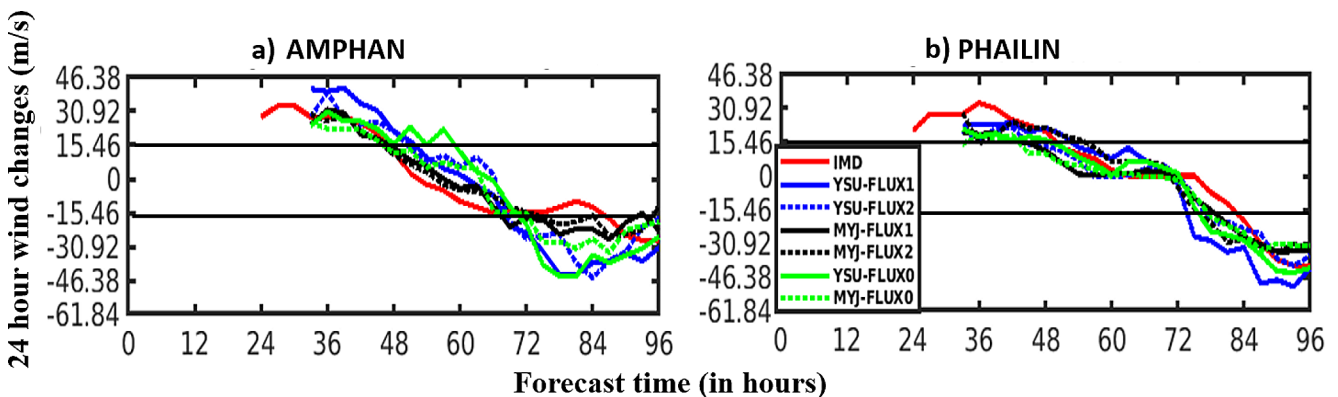

Fig. 3 The model simulated 24 h wind speed changes (in m/s) from all experiments along with IMD best-fit datasets (**a**) SuCS Amphan, and (**b**) ESCS Phailin

YSU-FLUX1, and YSU-FLUX2) were able to capture the pattern by displaying the ring of deep convection around the eyewall with the highest reflectivity values with small variations (Fig. 5). It is noted that all MYJ schemes (MYJ-FLUX0, MYJ-FLUX1, and MYJ-FLUX2) show underestimation in the spatial distribution of the maximum reflectivity pattern. The maximum reflectivity ranged up to 60 dBZ in the DWR image, as well matches with model prediction. However, all model experiments failed to capture the pattern of convective cells over the land as in the DWR image. The result suggested that the spatial coverage of maximum reflectivity is higher in the YSU-FLUX1 scheme, which is more consistent with observations. Similarly, for cyclone Phailin the model-predicted reflectivity from all experiments was compared with the IMD Visakhapatnam DWR observation at 16 UTC on 12 October 2013 (just before the landfall time) is illustrated in Fig. 6. The simulated reflectivity of the ESCS Phailin ranged between 46 dBZ to 60 dBZ, while the DWR shows a maximum reflectivity up to 50 dBZ. The model results of ESCS Phailin indicate that strong convective bands directed in the southwest direction matched well with the DWR observation, with relatively stronger convective activity along the Odisha coast and the adjoining coast of Andhra Pradesh. It is seen that the model is unable to capture the location of landfall with a centre position near latitude 19°N and longitude 85°E. Even though the eye is visible in all six experiments (YSU-FLUX0, YSU-FLUX1, YSU-FLUX2, MYJ-FLUX0, MYJ-FLUX1, MYJ-FLUX2). Results show that simulated reflectivity was over-estimated compared to the observation in all experiments.

In next Figs. (7–10) the temperature anomaly and wind pattern for both cases are derived and discussed from 3 best performing model experiments as considered in terms of MSW. Figure 7 depicts the azimuthally averaged temperature anomaly for SuCS Amphan at two distinct times, 15 UTC on 18 May and 03 UTC on 19 May 2020, through the centre of the cyclone with varying longitude and compared with satellite observation (CIRA; https://rammb-data.cira.colostate.edu/tc_realtime/). The satellite image from 15 UTC on 18 May (Fig. 7a) shows a warmer region between 9 km and 18 km with a magnitude of 2 °C to 7 °C, as well as an elevated upper warming of about 7 °C over a radial distance from centre to about 50 km. The observed data showed two colder regions, with heights below 8 km indicating a wider lower cooling and above 18 km indicating less upper cooling. Figure (7b-7d) shows that the YSU-FLUX2 and MYJ-FLUX1 simulations show a positive temperature anomaly with a maximum magnitude of 6 °C to 7 °C at heights ranging from 8 km to 12 km. Even though the YSU-FLUX1 experiment captured the maximum magnitude of the warm core region of magnitude 7 °C similar to observation, it captured the maximum warm core in two

different height between 4 km and 11 km, which is not consistent with observations. The YSU-FLUX1, YSU-FLUX2, and MYJ-FLUX1 experiments showed a limited spatial distribution of colder regions. However, MYJ-FLUX1 simulations better predict the stronger warming that ranges from 10 km to 13 km. Likewise, the radius-height section of the temperature anomaly for Amphan cyclone at 0300 UTC on 19 May 2020 is illustrated in Fig. 7e and h. The warmer core region is seen between 8 km and 18 km height in the satellite image taken at 03 UTC on 19 May 2020. A higher magnitude of 7°C is observed between 11 km and 14 km, and the colder region is located below 9 km. A positive temperature anomaly pattern with a magnitude from 2°C to 11°C is observed in model experiments between 3 km and 18 km. The negative anomalies is lower in the YSU-FLUX1 and MYJ-FLUX1 experiments. Even though YSU-FLUX2 captured more negative anomaly patterns but an entirely different pattern compared to observations. Model simulations tend to overestimate the warm core area in the upper troposphere by 1–3 °C when compared to satellite data. The results revealed a significant changes in the magnitude of temperature trends among the different combinations of PBL and air-sea flux schemes.

Figure 8 illustrates the temperature anomaly pattern of Phailin at 15 UTC on 11 OCT and 15 UTC on 12 OCT 2013, as taken by satellite observations and derived from model simulation results. The temperature anomaly from CIRA at 15 UTC on 11 October showed a significant warming of magnitude 6 °C between 12 km and 14 km and a lesser cooling below 9 km height (Fig. 8a). However, an overestimated strong warm core (8°C–10°C) region with height ranges ranging from 9 km to 15 km over a radial distance of roughly 20 km from the centre is indicated by model-predicted experiments. YSU-FLUX2 shows a stronger middle tropospheric warming of magnitude 8 °C closer to observation over a height of 9 km to 12 km. All model experiments show different tropospheric cooling patterns compared to observations. Figure 8e and h illustrates the predicted temperature anomaly of the ESCS Phailin, along with satellite observations. The observation figure (Fig. 8e) indicates a stronger middle tropospheric warming of magnitude 6 °C between 11 km and 15 km, with a radial distance of 80 km from the centre, which indicates the warming at the eye of the storm. The satellite image also depicts a wider, colder region below 8 km, indicating stronger cooling at low levels. The predicted results showed strong tropospheric warming for YSU-FLUX1, YSU-FLUX2, and MYJ-FLUX1, with values of 8 °C, 7 °C, and 8 °C, respectively. In contrast to observations, all the schemes (Fig. 8f and h) showed a sudden decrease in temperature anomaly, indicating stronger upper cooling after 16 km of height. The YSU-FLUX1 Scheme has a strong middle tropospheric
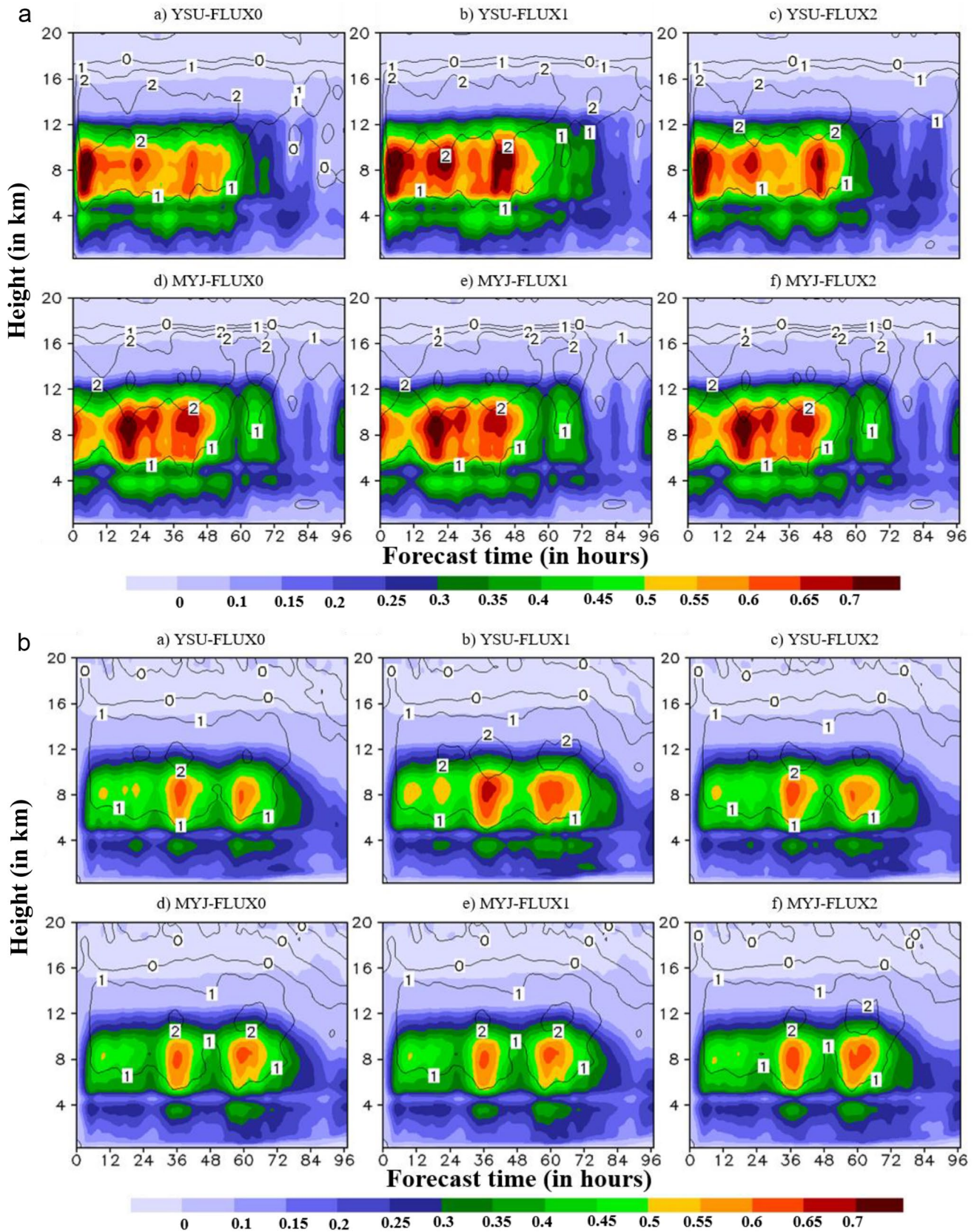
Fig. 4 a) Time variation of microphysics latent heating (in shaded, 10^{-3} Ks^{-1}) and divergence (in contour, 10^{-5} s^{-1}) from all experiments for SuCS Amphan by takin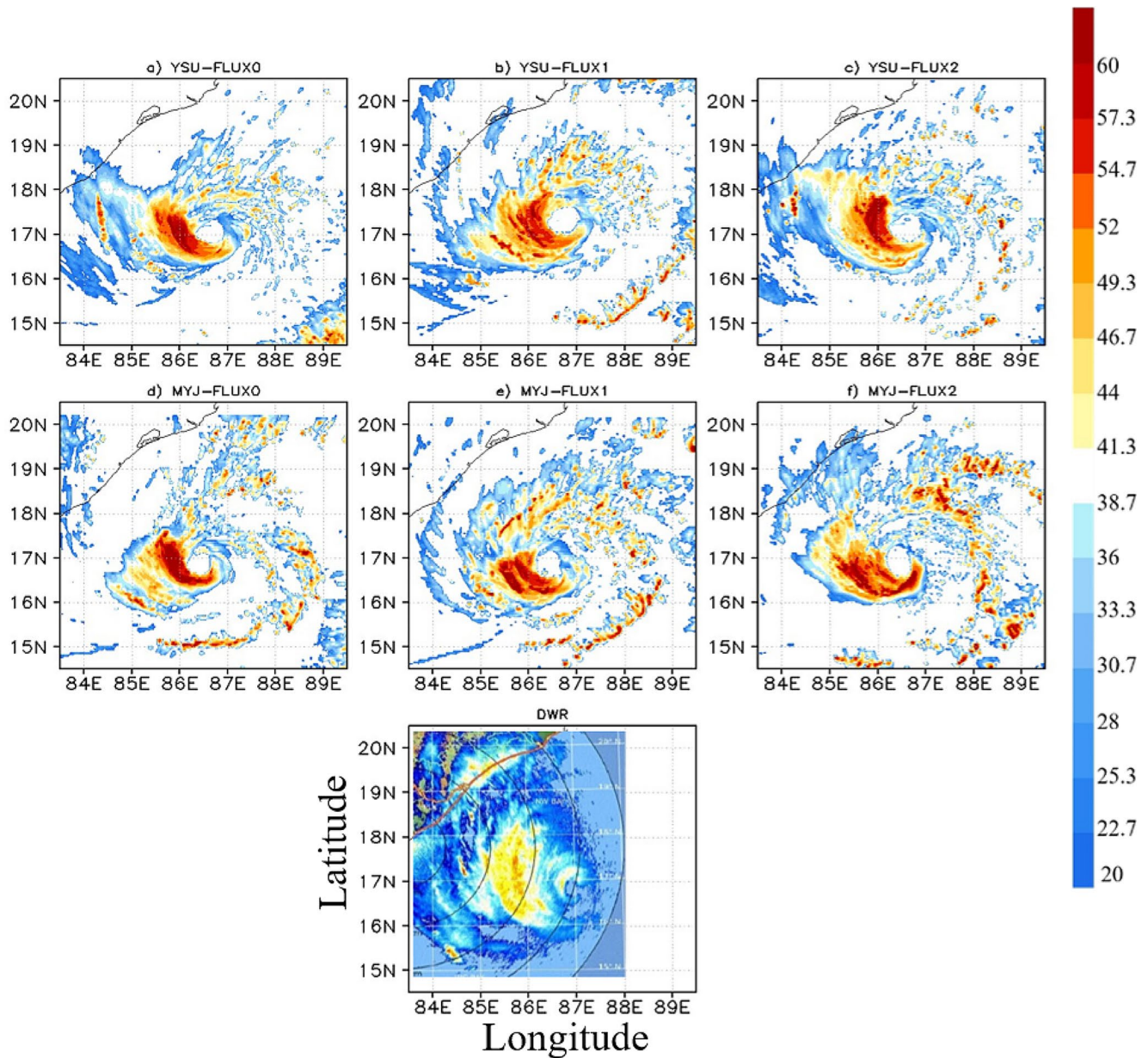g the area average over the D03 region. **b)** Time variation of microphysics latent heating (in shaded, 10^{-3} Ks^{-1}) and divergence (in contour, 10^{-5} s^{-1}) from all experiments for ESCS Phailin by taking the area average over the D03 region

Fig. 5 Maximum reflectivity (in dBZ) of about 0900 UTC on 19 May 2020 of SuCS Amphan was obtained from model prediction along with the Visakhapatnam DWR image

warming of magnitude closer to observation. Typically, the warm core structure in most of the model results spans a range of 6 km to 16 km. However, the CIRA satellite image shows the warm core fluctuating between 10 km and 16 km.

Figure 9 shows the Wind speed for SuCS Amphan at two different times (12 UTC on 18 May and 15 UTC on 18 May 2020), obtained from the satellite observation (CIRA; https://rammb-data.cira.colostate.edu/tc_realtime/about.asp#mpsatwnd) and model experiments at 700 hPa (Kumar et al. 2011). Both CIRA wind patterns and the model-predicted results over the 2×2-degree from centre of cyclone show that the eye had a circular pattern. The observed

figure from CIRA indicates a maximum wind speed magnitude about 80–95 knots at 12 UTC on 18 May and a wind speed maximum of 80–110 knots at 15 UTC on 18 May were noticed between 14°N and 15°N. The results show that the model at 1.667 km can represent the maximum wind pattern of magnitude greater than 95 knots (as marked black in simulated results) concentrated around the centre region. The high-resolution WRF-ARW model with moving nested domains successfully captured the spatial pattern of wind speeds ranging from 50 to 85 knots. The model overestimated the maximum wind pattern which was about 80–110 knots compared to CIRA satellite observations. In
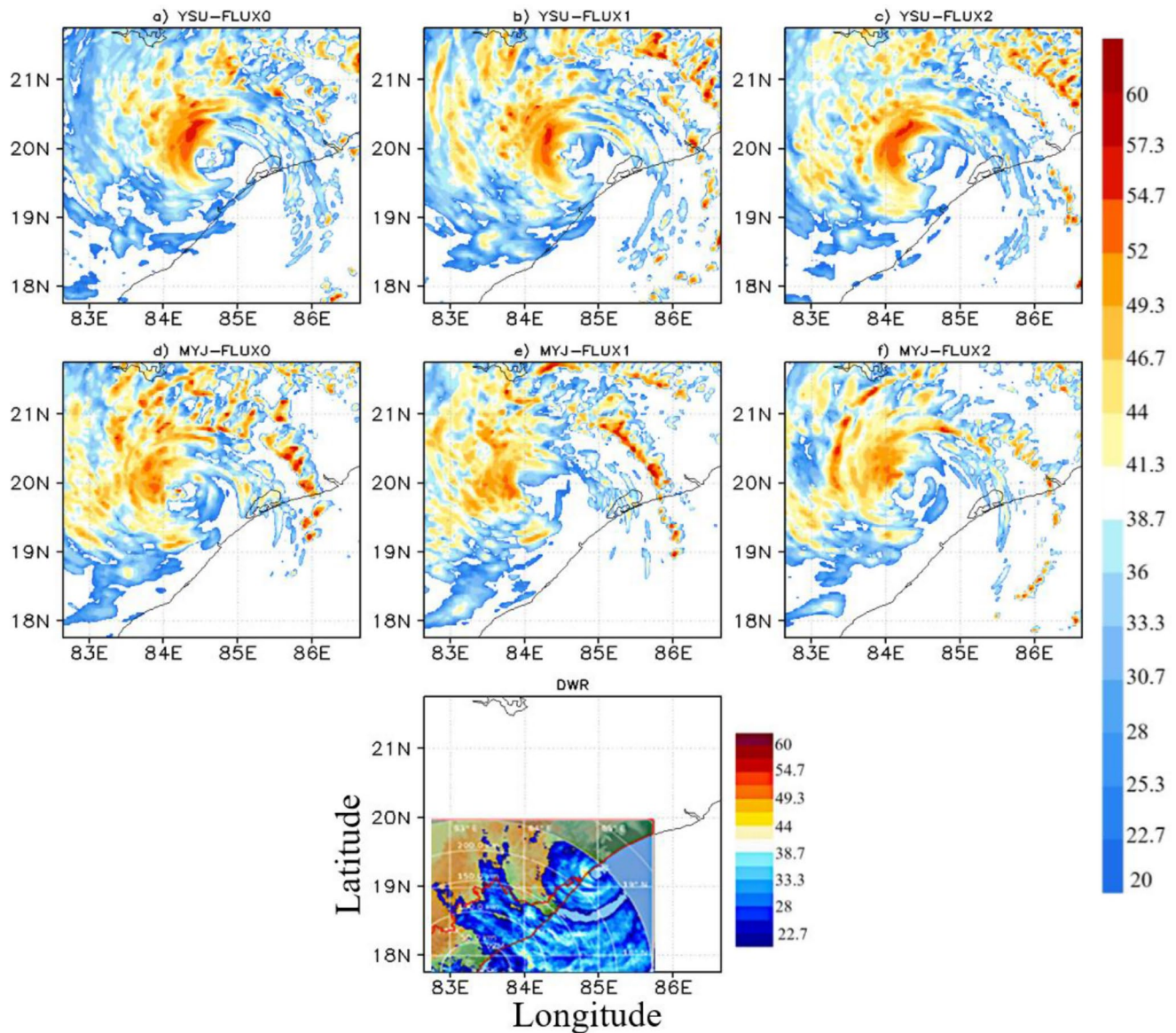
Fig. 6 Maximum reflectivity (in dBZ) about 1600 UTC on 12 October 2013 of ESCS Phailin obtained from model simulations along with Visakhapatnam DWR image

all experiments, the weather symbol (in red color) denotes the model-predicted storms centre. The computed displacement error was lower for MYJ-FLUX1 and MYJ-FLUX2, measuring about 66 km at 12 UTC and 56 km at 15 UTC on 18 May 2020, respectively. Similarly, Fig. 10 represents the wind structure pattern for cyclone Phailin at 06 UTC on 11 OCT and 00 UTC on 12 OCT 2013. The model-predicted results were compared with CIRA observations. The CIRA wind indicates that a wind maximum of magnitude 80–110 knots is located around the centre of the Phailin cyclone at both times. The CIRA wind pattern's centre position was located between 16°N and 17°N at 06 UTC on 11 October and between 17°N and 18°N at 00 UTC on 12 October 2013 and both satellite figures depict a 35-knot surface wind

spatial region. The high-resolution WRF-ARW model captured a strong wind pattern of 65–85 knots with a circular, symmetric pattern similar to observations. Still, it could not capture the surface wind pattern of 35 knots. The results also indicated that MYJ-FLUX1 well captured the central location (88.1E and 16.1 N) at 06 UTC on 11 OCT, and all models failed to capture the centre position (86.4E and 17.4 N) of wind patterns at 00 UTC on 12 OCT 2013. The result suggested that PBL and air-sea flux schemes have an apparent effect on the structure of ESCS and SuCS in a high-resolution WRF-ARW modeling system.

Fig. 7 Temperature anomaly for SuCS Amphan at 15 UTC on 18 May 2020 (left panel) and 03 UTC on 19 May 2020 (right panel) obtained from the satellite observation and model experiments (considered from the centre of the cyclone to 600 km varying longitude)
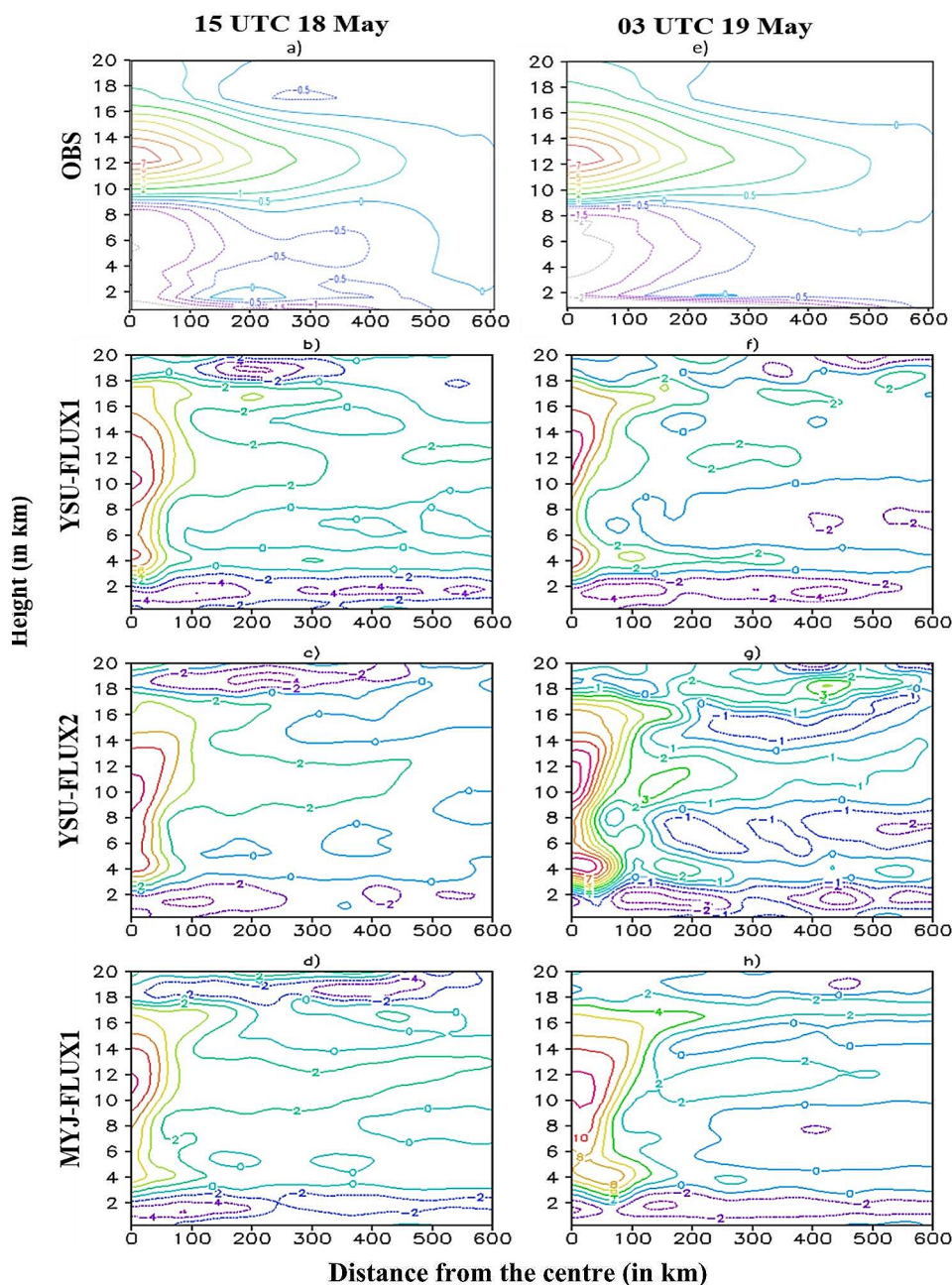

Impact on track forecast

Figure 11 depicts the observed IMD track with the six model-predicted tracks at every 3 h data for SuCS Amphan and ESCS Phailin over the Bay of Bengal. The observed track of Amphan from 17 May to 21 May 2020) shows north to north-eastward movement, and Phailin from 12 UTC on 09 OCT to 12 UTC on 13 OCT 2013) shows a west-north-westward movement to north-westward movement. Most of the Amphan tracks predicted by the model exhibit similar patterns and are in good agreement with the IMD. Each model-predicted track shows slight deviations of less than

100 km immediately before the landfall, and the movement significantly slows down towards the end of the simulation period. YSU-FLUX0 and MYJ-FLUX0 better captured the Amphan landfall location with a landfall error of about 17 km, while the YSU-FLUX1 scheme predicts the landfall time with a 5-hour delay to IMD (Table 3). Model-predicted tracks of ESCS Phailin were very close to observation during the entire simulation period, but MYJ-FLUX0 and MYJ-FLUX1 diverged left by the observed track at the end of the simulation period with a higher mean track error of about 64 km. As per the IMD track, Phailin moved across Odisha and the area near Gopalpur, Odisha, on the nearby coastline

Fig. 8 Temperature anomaly for the ESCS Phailin at 15 UTC on 11 OCT 2013 (left panel) and 15 UTC on 12 OCT 2013 (right panel) obtained from the satellite observation and model experiments (considered from the center of the cyclone to 600 km varying longitude)
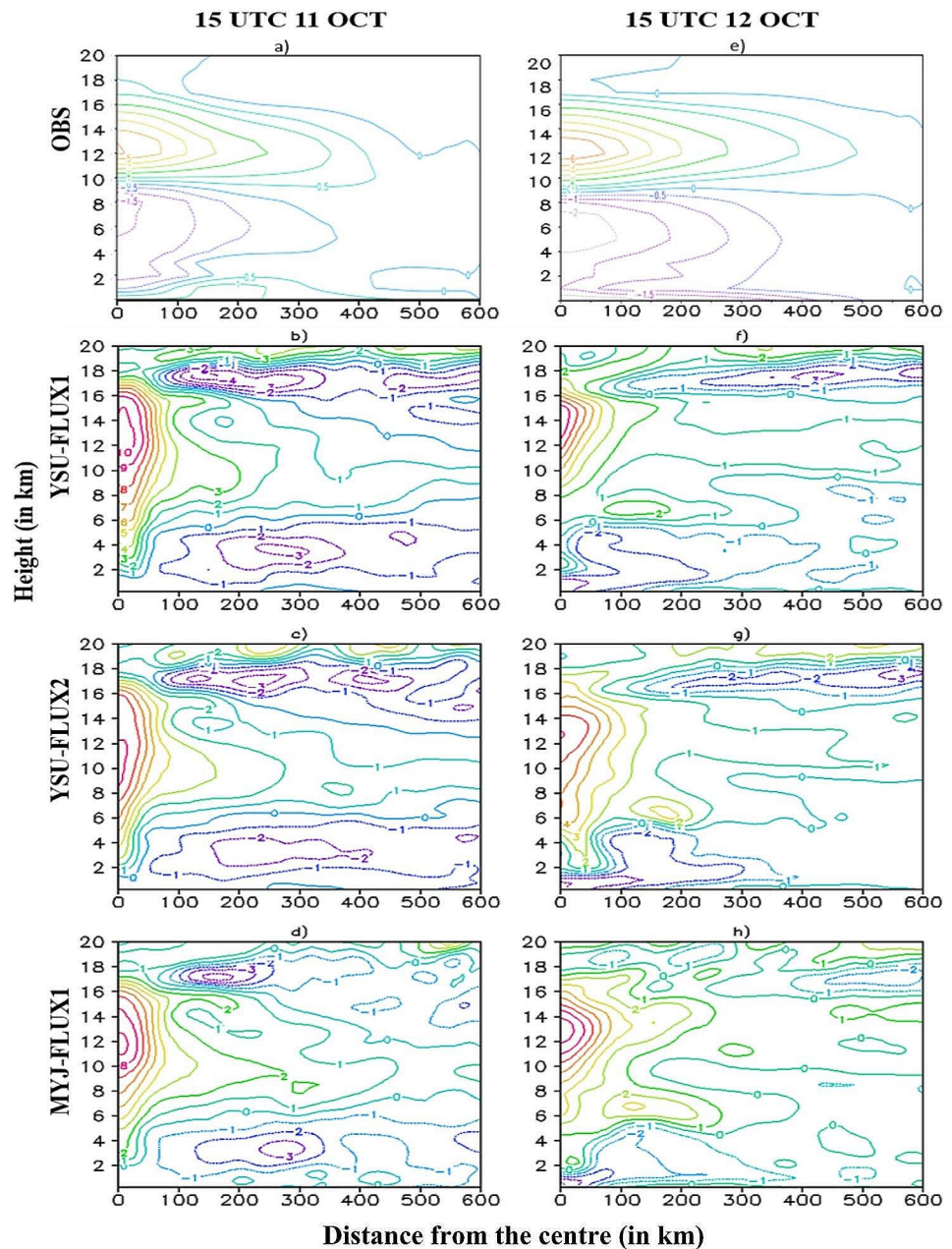

of north Andhra Pradesh. Even though all cases tried to capture the landfall position of Phailin, whereas MYJ-FLUX1 accurately predicted the landfall location with less error of 11 km, and the landfall time is better predicted in all YSU cases compared to all MYJ cases with a 5-hour before to the observation (Table 3). Results from model experiments suggested that the movement of ESCS Phailin was faster, and landfall time errors varying from 5 to 7 h, while the movement of SuCS Amphan was slowly, and landfall time errors varying between 5 and 9 h. The average track errors are 64 km, 63 km, 65 km, 74 km, 78 km, and 75 km for the six experiments YSU-FLUX0, YSU-FLUX1, YSU-FLUX2, MYJ-FLUX0, MYJ-FLUX1, and MYJ-FLUX2 (Table 2).

As a result of the experiments taken into consideration, the YSU-FLUX1 experiment produces better track forecasts with the least amount of track error, and experiment MYJ-FLUX1 shows greater track error. Finally, the study implies that YSU and MYJ simulations produce the least and largest track errors, respectively (similar to Rajeswari et al. 2020).

Impact of sea surface temperature (SST) on the intensity

Studies (Mohanty et al. 2019; Rai et al. 2019) suggested that cyclone forecast improved using SST update in the numerical weather prediction model, and TC intensity will decrease

Fig. 9 Wind speed (in knots) for Amphan at 12 UTC on 18 May 2020 (left panel) and 15 UTC on 18 May 2020 (right panel), obtained from the observation and model experiments
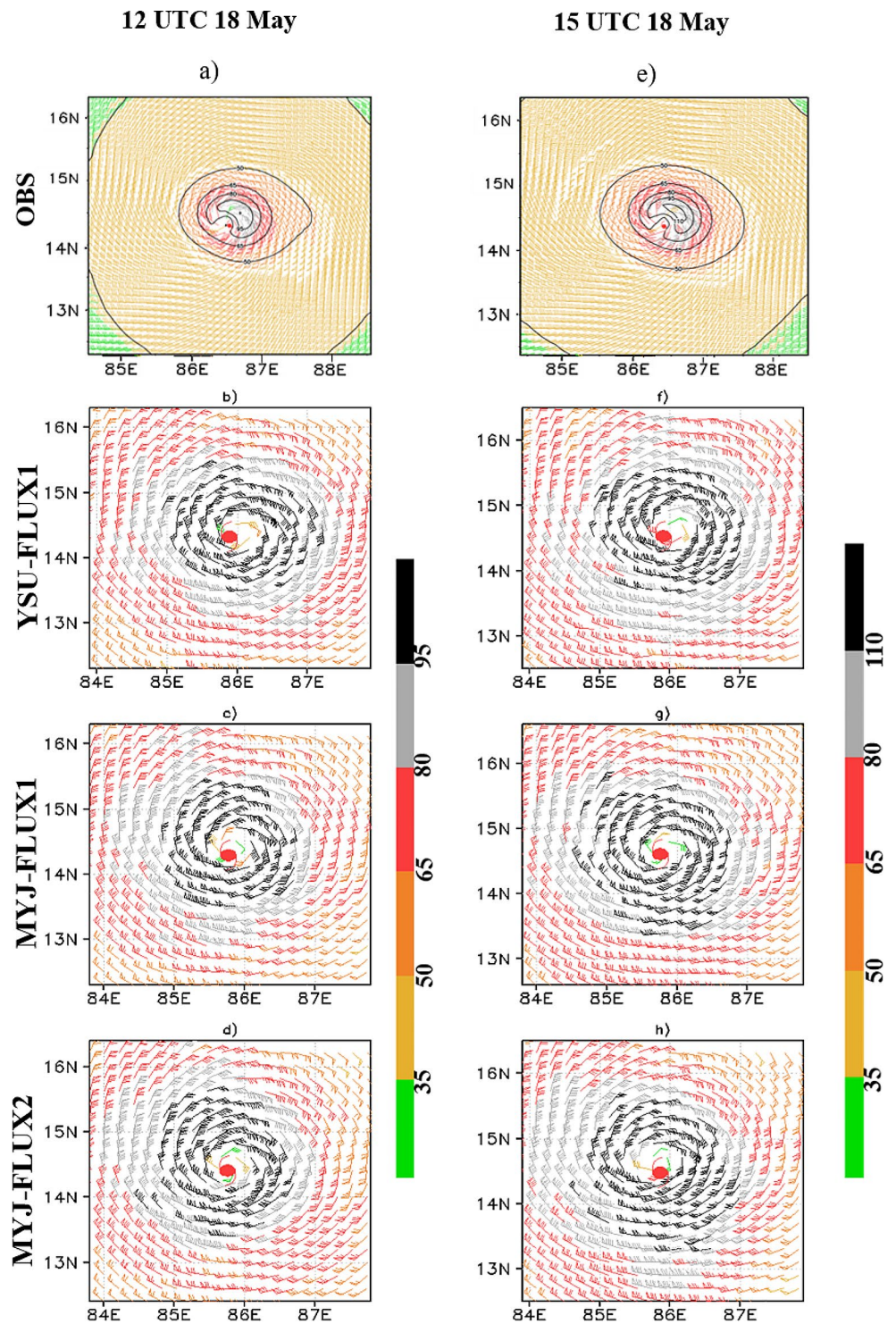
as a result of SST cooling (Wang et al. 2004). Therefore, this study also includes an analysis of the effects of SST in more intensified (over-estimated) cases, using 1.667 km horizontal resolution under moving nested domain. Based on the results as discussed in Sect. 3.1, it was observed that YSU PBL scheme provided over-estimation in MSW forecast (Fig. 2) and hence, four additional experiments with

YSU-FLUX1 and YSU-FLUX2 for both cases have been conducted to examine the effect of SST. Figure 12 depicts the model-predicted intensity (MSW and MSLP) with and without SST, and compared with IMD best-fit track data for both cases SuCS Amphan and ESCS Phailin. The maximum intensity (in terms of MSW) of Amphan cyclone in YSU-FLUX1 experiment was about 86 m/s and while in

Fig. 10 Wind speed (in knots) for Phailin at 06 UTC on 11 OCT 2013 (left panel) and 00 UTC on 12 OCT 2013 (right panel) obtained from the observation and model experiments
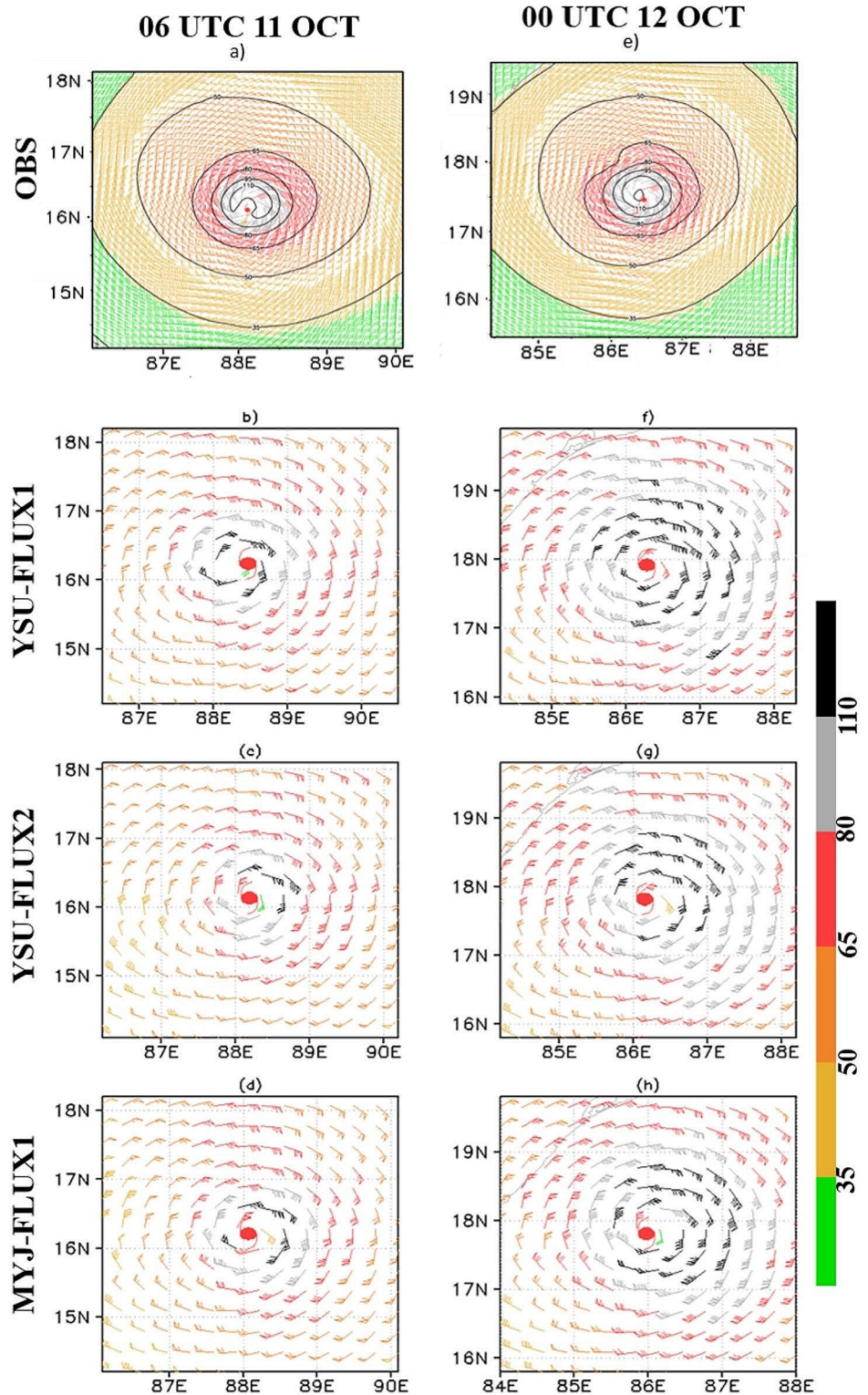
YSU-FLUX1-SST showed a maximum intensity of about 75 m/s. Similarly in the experiments YSU-FLUX2 and YSU-FLUX2-SST had a maximum intensity of 79 m/s and 60 m/s. Which clearly indicated that after using SST the simulated MSW were close to the observation. Similarly, results suggested that in case of Phailin cyclone, the simulated maximum intensity for MSW was about 73 m/s and 61 m/s in YSU-FLUX1 and YSU-FLUX2 experiments

Fig. 11 Observed best-fit track from IMD along with model simulated tracks of SuCS Amphan (left) and ESCS Phailin (right) over the Bay of Bengal region
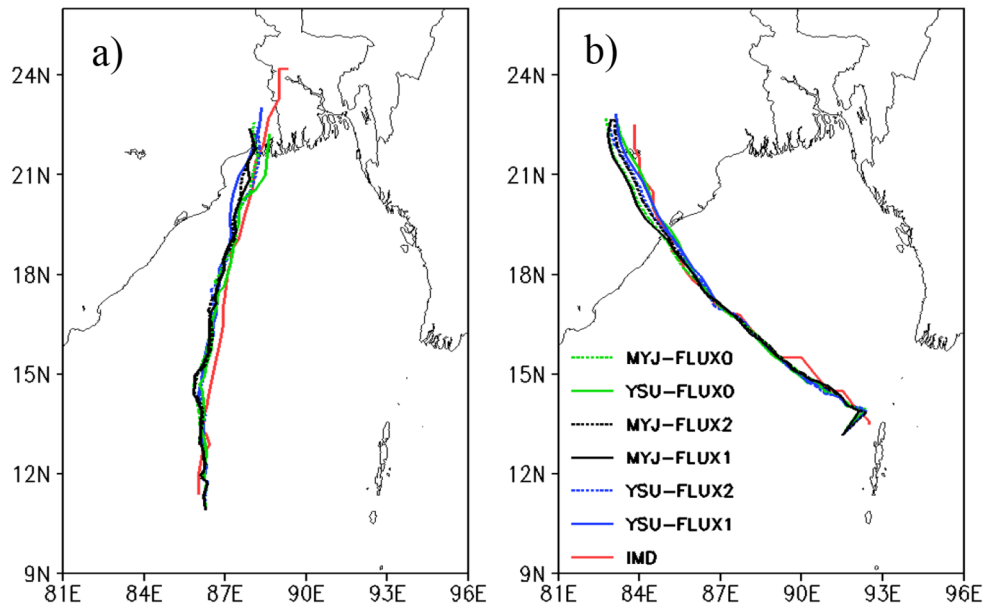

Table 3 Simulated landfall [position (in km) and time (in hours)] errors with different experiments

	YSU-FLUX0	YSU-FLUX1	YSU-FLUX2	MYJ-FLUX0	MYJ-FLUX1	MYJ-FLUX2
Amphan	17 km	67 km	20 km	17 km	78 km	37 km
	(-9 h)	(-5 h)	(-9 h)	(-7 h)	(-7 h)	(-9 h)
Phailin	35 km	25 km	16 km	16 km	11 km	31 km
	(+5 h)	(+5 h)	(+5 h)	(+7 h)	(+7 h)	(+7 h)

+ (-) indicates faster (slower) movement in simulations compared to IMD best-fit track datasets
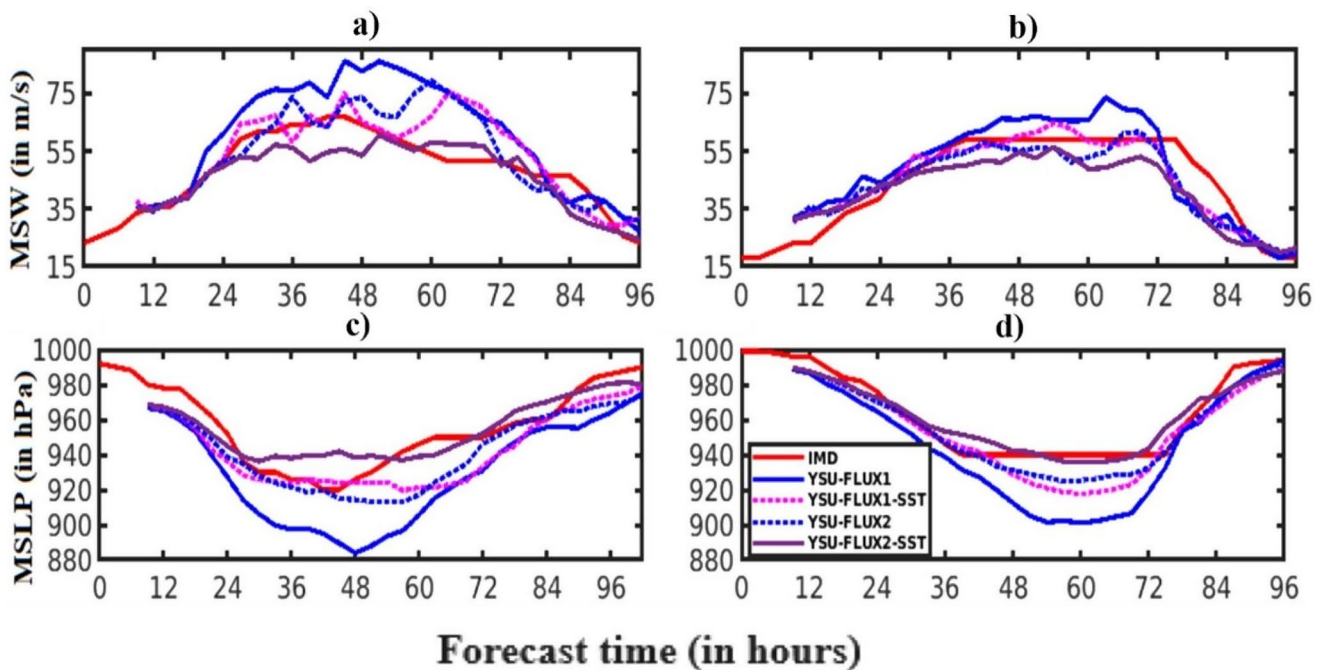

Fig. 12 Time variation of model simulated MSW (in m/s) and MSLP (in hPa) with and without SST along with IMD best-fit track data (**a** & **c**) for SuCS Amphan, and (**b** & **d**) for ESCS Phailin, respectively

respectively. But in experiments with YSU-FLUX1-SST and YSU-FLUX2-SST the wind speed decreased and maximum intensity was about 64 m/s and 56 m/s respectively. Results suggested that updated SST in YSU-FLUX1 experiment provided a better forecast of the storm intensity. The mean intensity error in YSU-FLUX1 experiment was about 9.37 m/s, 19 hPa and that was about 5.8 m/s, 10 hPa in YSU-FLUX1-SST experiment. Finally, the result suggested that updated SST experiment with YSU-FLUX1 provided a better forecast of the intensity.

Conclusions

This work has divided in two folds, in the first fold the impact of two PBL (YSU and MYJ) and three air-sea flux (FLUX0, FLUX1, and FLUX2) parametrization schemes were used to forecast of SuCS Amphan and ESCS Phailin, which developed over the Bay of Bengal. In the second fold, the time-varying SST was updated in those simulations, which provided an over-prediction in the storm intensity in terms of MSW. The WRF-ARW model was used to predict the track, intensity, and storm structures at a cloud-resolving scale with a horizontal resolution of 1.667 km. The simulated results were compared with available IMD best-fit track observations, storm structures from CIRA, and Visakhapatnam DWR. The summary of the results can be concluded as follows:

- The forecasted intensity (in terms of MSW) was better with the MYJ-FLUX2 and MYJ-FLUX1 experiments, and the mean absolute errors were about 2 m/s, 2 m/s, 7 m/s, and 9 m/s from day-1 to day-4, followed by the MYJ-FLUX1 experiment, with this error being about 2 m/s, 4 m/s, 4 m/s, and 2 m/s, respectively.
- The experiments with YSU PBL scheme over-predicted the MSW pattern, when using without SST. Once time-varying SST datasets updated with YSU experiments, then intensity was reduced in the simulations. The YSU-FLUX1 experiment with updated SST brought it closer to IMD, with daily errors form day-1 to day-4 was about 2 m/s, 1 m/s, 6 m/s, and 6 m/s. However, without SST these errors were 7 m/s, 13 m/s, 6 m/s, and 4 m/s from day-1 to day-4.
- The MYJ-FLUX1 and MYJ-FLUX2 experiments accurately predict the rapid intensification and dissipation. The non-local YSU experiments more accurately estimated the maximum reflectivity pattern of both Amphan and Phailin cyclones. The pattern of latent heating and upper-level divergence was consistent and correlated with the MSW.

- The results from the warm core structure in terms of temperature anomaly, surface wind pattern of both cases suggested that the model was able to well resolve the structures of the storms. In most of the simulated cases, the warm core structure varies from 6 km to 16 km, whereas in the observation from CIRA, the warm core varies from 10 km to 16 km. Similarly, results from the simulated wind pattern suggest that the patterns were well resolved in terms of spatial and magnitude in the model, but with more coverage area for the maximum wind near the vortex of the storms.
- The WRF-ARW model successfully predicted the tracks of both cyclones Amphan and Phailin using different PBL and ASF experiments and the YSU-FLUX1 experiment is closer to the observation with a lower mean track error of about 63 km, while MYJ-FLUX1 shows a higher track error about 78 km.
- The least mean track errors for both cases on day-1 to day-4 were about 40 km, 38 km, 64 km, and 125 km in the experiment with YSU-FLUX1, followed by YSU-FLUX0 respectively. In all of the experiments, the SuCS Amphan moved more slowly (ranging from 5 to 9 h), and the ESCS Phailin moved faster (ranging from 5 to 7 h) during landfall. The landfall position error of SuCS Amphan ranges from 17 km to 78 km, while ESCS Phailin varies from approximately 11 km to 35 km.
- Overall, the results suggest that a high-resolution modeling system in the cloud resolving scale of about 1.667 km resolution were sensitive with varying PBL and ASF including SST in forecast of intensity, rapid intensification, storm structures in terms of maximum reflectivity, wind pattern, vertical profile of temperature anomalies over the Bay of Bengal region. The results can be improved further through data assimilation and a coupled atmosphere-ocean modeling system.

Author contributions The authors contributed to the study's conception and design. Material preparation, data collection, analysis, first draft of the manuscript was written by [Kuvar Satya Singh, and Reshma M.S.]. Conceptualization, Methodology, Formal analysis and investigation, Writing - review and editing: [Kuvar Satya Singh, and Reshma M.S.]

Data availability The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

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

References

Ahmed R, Mohapatra M, Dwivedi S, Giri RK (2021) Characteristic features of Super Cyclone 'AMPHAN'- observed through satellite images. Trop Cyclone Res Rev 10:16–31. https://doi.org/10.1016/j.tcrr.2021.03.003

Chatterjee S, Roy S (2021) A complete study on the Costliest Super Cyclone Amphan (May 2020) with its devastating impact on West Bengal, India. Remote Sens Earth Syst Sci 4:249–263. https://doi.org/10.1007/s41976-022-00066-5

Chen SS, Price JF, Zhao W et al (2007) The CBLAST-Hurricane Program and the Next-Generation fully coupled Atmosphere–Wave–Ocean models for Hurricane Research and Prediction. Bull Am Meteorol Soc 88:311–318. https://doi.org/10.1175/BAMS-88-3-311

Chen X, Xue M, Fang J (2018) Rapid Intensification of Typhoon Mujigae (2015) under different sea surface temperatures: structural changes leading to Rapid Intensification. J Atmos Sci 75:4313–4335. https://doi.org/10.1175/JAS-D-18-0017.1

Das MK, Chowdhury MA, Das S (2015) Sensitivity study with physical parameterization schemes for simulation of mesoscale convective systems associated with squall events. Int J Earth Atmospheric Sci 2:20–36

Das Y, Mohanty UC, Jain I (2016) Development of tropical cyclone wind field for simulation of storm surge/sea surface height using numerical ocean model. Model Earth Syst Environ 2:1–22. https://doi.org/10.1007/s40808-015-0067-5

Davis C, Wang W, Chen SS et al (2008) Prediction of Landfalling hurricanes with the Advanced Hurricane WRF Model. Mon Weather Rev 136:1990–2005. https://doi.org/10.1175/2007MWR2085.1

Deshpande M, Singh VK, Ganadhi MK et al (2021) Changing status of tropical cyclones over the north Indian Ocean. Clim Dyn 57:3545–3567. https://doi.org/10.1007/s00382-021-05880

Donelan MA, Haus BK, Reul N et al (2004) On the limiting aerodynamic roughness of the ocean in very strong winds. Geophys Res Lett 31. https://doi.org/10.1029/2004GL019460

Dudhia J (1989) Numerical Study of Convection observed during the Winter Monsoon Experiment using a Mesoscale two-Dimensional Model. J Atmos Sci 46:3077–3107. https://doi.org/10.1175/1520-0469

Ek MB, Mitchell KE, Lin Y et al (2003) Implementation of Noah land surface model advances in the National Centers for Environmental Prediction operational mesoscale Eta model. J Geophys Research: Atmos 108:8851. https://doi.org/10.1029/2002JD003296

Emanuel K, Zhang F (2016) On the predictability and error sources of tropical cyclone intensity forecasts. J Atmos Sci 73:3739–3747. https://doi.org/10.1175/JAS-D-16-0100.1

Gogoi RB, Kutty G, Borgohain A (2022) Impact of INSAT-3D satellite-derived wind in 3DVAR and hybrid ensemble-3DVAR data assimilation systems in the simulation of tropical cyclones over the Bay of Bengal. Model Earth Syst Environ 8:1813–1823. https://doi.org/10.1007/s40808-021-01183-8

Gopalakrishnan SG, Marks F, Zhang JA et al (2013) A study of the impacts of Vertical Diffusion on the structure and intensity of the Tropical cyclones using the high-resolution HWRF system. J Atmos Sci 70:524–541. https://doi.org/10.1175/JAS-D-11-0340.1

Greeshma M, Srinivas CV, Hari Prasad KBRR et al (2019) Sensitivity of tropical cyclone predictions in the coupled atmosphere–ocean model WRF-3DPWP to surface roughness schemes. Meteorol Appl 26:324–346. https://doi.org/10.1002/met.1765

Hong SY, Noh Y, Dudhia J (2006) A New Vertical Diffusion Package with an Explicit treatment of entrainment processes. Mon Weather Rev 134:2318–2341. https://doi.org/10.1175/MWR3199.1

Hossain MS, Samad MA, Hossain MS et al (2022) The sensitivity of initial Condition and Horizontal Resolution on Simulation of Tropical Cyclone Amphan over the Bay of Bengal using WRF-ARW Model. Dhaka Univ J Sci 69:202–211. https://doi.org/10.3329/dujs.v69i3.60031

Huang CY, Lin JY, Kuo HC, Chen DS et al (2022) A numerical study for Tropical Cyclone Atsani (2020) past offshore of southern Taiwan under topographic influences. Atmosphere 13:618. https://doi.org/10.3390/atmos13040618

Janjic ZI (1994) The step-mountain eta coordinate model: further developments of the convection, viscous sublayer, and turbulence closure schemes. Mon Weather Rev 122:927–945. https://doi.org/10.1175/1520-0493(1994)122%3C0927:TSMECM%3E2.0.CO;2

Kain JS (2004) The Kain-Fritsch Convective parameterization: an update. J Appl Meteorol 43:170–181. https://doi.org/10.1175/1520-0450(2004)043%3C0170:TKCPAU%3E2.0.CO;2

Kalra S, Kumar S, Routray A (2019) Simulation of heavy rainfall event along east coast of India using WRF modeling system: impact of 3DVAR data assimilation. Model Earth Syst Environ 5:245–256. https://doi.org/10.1007/s40808-018-0531-0

Kanada S, Wada A, Nakano M, Kato T (2012) Effect of planetary boundary layer schemes on the development of intense tropical cyclones using a cloud-resolving model. J Geophys Research: Atmos 117. https://doi.org/10.1029/2011JD016582

Kanase RD, Salvekar PS (2015) Effect of physical parameterization schemes on track and intensity of cyclone LAILA using WRF model. Asia Pac J Atmos Sci 51:205–227. https://doi.org/10.1007/s13143-015-0071-8

Kattamanchi VK, Viswanadhapalli Y, Dasari HP et al (2021) Impact of assimilation of SCATSAT-1 data on coupled ocean-atmospheric simulations of tropical cyclones over Bay of Bengal. Atmos Res 261:105733. https://doi.org/10.1016/j.atmosres.2021.105733

Knaff JA, DeMaria M, Molenar DA et al (2011) An Automated, Objective, multiple-Satellite-platform Tropical Cyclone surface wind analysis. J Appl Meteorol Climatol 50:2149–2166. https://doi.org/10.1175/2011JAMC2673.1

Kueh MT, Chen WM, Sheng YF, Typhoon Haiyan (2019) Effects of horizontal resolution and air-sea flux parameterization on the intensity and structure of simulated (2013). Natural Hazards and Earth System Sciences 19:1509–1539. https://doi.org/10.5194/nhess-19-1509-2019

Kumar A, Done J, Dudhia J et al (2011) Simulations of Cyclone Sidr in the Bay of Bengal with a high-resolution model: sensitivity to large-scale boundary forcing. Meteorol Atmos Phys 114:123–137. https://doi.org/10.1007/s00703-011-0161-9

Kutty G, Gogoi R, Rakesh V, Pateria M (2020) Comparison of the performance of HYBRID ETKF-3DVAR and 3DVAR data assimilation scheme on the forecast of tropical cyclones formed over the Bay of Bengal. J Earth Syst Sci 129:1–4. https://doi.org/10.1007/s12040-020-01497-8

Lengaigne M, Neetu S, Samson G et al (2019) Influence of air–sea coupling on Indian Ocean tropical cyclones. Clim Dyn 52:577–598. https://doi.org/10.1007/s00382-018-4152-0

Li S, Chen C (2022) Air-sea Interaction processes during Hurricane Sandy: coupled WRF-FVCOM model simulations. Prog Oceanogr 206:102855. https://doi.org/10.1016/j.pocean.2022.102855

Liao X, Li T, Ma C (2022) Moist Static Energy and secondary circulation evolution characteristics during the Rapid Intensification of

Super Typhoon Yutu (2007). Atmos (Basel) 13:1105. https://doi.org/10.3390/atmos13071105

Lin YL, Farley RD, Orville HD (1983) Bulk parameterization of the snow field in a cloud model. J Clim Appl Meteorol 22:1065–1092. https://doi.org/10.1175/1520-0450

Lok CCF, Chan JCL, Toumi R (2022) Importance of Air-Sea Coupling in simulating Tropical Cyclone intensity at Landfall. Adv Atmos Sci 39:1777–1786. https://doi.org/10.1007/s00376-022-1326-9

Mandal M, Singh KS, Balaji M, Mohapatra M (2016) Performance of WRF-ARW model in real-time prediction of Bay of Bengal cyclone 'Phailin'. Pure Appl Geophys 173:1783–1801. https://doi.org/10.1007/s00024-015-1206-7

Mittal R, Tewari M, Radhakrishnan C et al (2019) Response of tropical cyclone phailin (2013) in the Bay of Bengal to climate perturbations. Clim Dyn 53:2013–2030. https://doi.org/10.1007/s00382-019-04761-w

Mlawer EJ, Taubman SJ, Brown PD et al (1997) Radiative transfer for inhomogeneous atmospheres: RRTM, a validated correlated-k model for the longwave. J Geophys Research: Atmos 102:16663–16682. https://doi.org/10.1029/97JD00237

Mohanty S, Nadimpalli R, Osuri KK et al (2019) Role of Sea Surface temperature in modulating life cycle of Tropical Cyclones over Bay of Bengal. Trop Cyclone Res Rev 8:68–83. https://doi.org/10.1016/j.tcrr.2019.07.007

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 122:589–601. https://doi.org/10.1007/s12040-013-0291-1

Moon J, Park J, Cha DH (2021) Does increasing Model Resolution improve the real-time forecasts of Western North Pacific Tropical Cyclones? Atmos (Basel) 12:776. https://doi.org/10.3390/atmos12060776

Nahar S, Quadir DA, Mannan MA, Shuvo SD (2022) Prediction of track of Super Cyclone Amphan using WRF-ARW Model. Dhaka Univ J Earth Environ Sci 10:35–42. https://doi.org/10.3329/dujees.v10i2.57513

Nekkali YS, Osuri KK, Das AK (2022) Numerical modeling of tropical cyclone size over the Bay of Bengal: influence of microphysical processes and horizontal resolution. Meteorol Atmos Phys 134:72. https://doi.org/10.1007/s00703-022-00915-4

Nellipudi NR, Viswanadhapalli Y, Challa VS et al (2021) Impact of surface roughness parameterizations on tropical cyclone simulations over the Bay of Bengal using WRF-OML model. Atmos Res 262:105779. https://doi.org/10.1016/j.atmosres.2021.105779

Njuki SM, Mannaerts CM, Su Z (2022) Influence of Planetary Boundary Layer (PBL) Parameterizations in the Weather Research and forecasting (WRF) model on the Retrieval of Surface Meteorological Variables over the Kenyan highlands. Atmos (Basel) 13:169. https://doi.org/10.3390/atmos13020169

Park J, Cha DH, Lee MK et al (2020) Impact of Cloud Microphysics schemes on Tropical Cyclone Forecast over the western North Pacific. J Geophys Research: Atmos 125. https://doi.org/10.1029/2019JD032288

Pattanayak S, Mohanty UC, Osuri KK (2012) Impact of parameterization of physical processes on Simulation of Track and Intensity of Tropical Cyclone Nargis (2008) with WRF-NMM model. Sci World J 2012:1–18. https://doi.org/10.1100/2012/671437

Powell MD, Vickery PJ, Reinhold TA (2003) Reduced drag coefficient for high wind speeds in tropical cyclones. Nature 422:279–283. https://doi.org/10.1038/nature01481

Pradhan PK, Kumar V et al (2021) Demonstration of the temporal evolution of tropical cyclone phailin using gray-zone simulations and decadal variability of cyclones over the Bay of Bengal in a warming climate. Oceans 2:648–674. https://doi.org/10.3390/oceans2030037

Rai D, Pattnaik S, Rajesh PV, Hazra V (2019) Impact of high resolution sea surface temperature on tropical cyclone characteristics over the Bay of Bengal using model simulations. Meteorol Appl 26:130–139. https://doi.org/10.1002/met.1747

Rajeswari JR, Srinivas CV, Mohan PR, Venkatraman B (2020) Impact of Boundary Layer Physics on Tropical Cyclone simulations in the Bay of Bengal using the WRF Model. Pure Appl Geophys 177:5523–5550. https://doi.org/10.1007/s00024-020-02572-3

Raju PV, Potty J, Mohanty UC (2011) Sensitivity of physical parameterizations on prediction of tropical cyclone Nargis over the Bay of Bengal using WRF model. Meteorol Atmos Phys 113:125–137. https://doi.org/10.1007/s00703-011-0151-y

Rizza U, Canepa E, Miglietta MM et al (2021) Evaluation of drag coefficients under medicane conditions: coupling waves, sea spray and surface friction. Atmos Res 247:105207. https://doi.org/10.1016/j.atmosres.2020.105207

Roy C, Rahman MR, Ghosh MK, Biswas S (2024) Tropical cyclone intensity forecasting in the Bay of Bengal using a biologically inspired computational model. Model Earth Syst Environ 10:523–537. https://doi.org/10.1007/s40808-023-01786-3

Sahoo B, Bhaskaran PK (2016) Assessment on historical cyclone tracks in the Bay of Bengal, east coast of India. Int J Climatol 36:95–109. https://doi.org/10.1002/joc.4331

Singh KS, Thankachan A, Thatiparthi K et al (2022) Prediction of rapid intensification for land-falling extremely severe cyclonic storms in the Bay of Bengal. Theor Appl Climatol 147:1359–1377. https://doi.org/10.1007/s00704-022-03923-x

Singh KS, Nayak S, Maity S et al (2023) Prediction of extremely severe cyclonic storm Fani. Using Mov Nested Domain Atmos (Basel) 14:637. https://doi.org/10.3390/atmos14040637

Skamarock WC, Klemp JB, Dudhia J, Gill DO, Liu Z, Berner J, Wang W, Powers JG, Duda MG, Barker DM, Huang XY (2019) A description of the advanced research WRF model version 4 National Center for Atmospheric Research: Boulder CO, USA. 145:550

Tang J, Zhang JA, Kieu C, Marks FD (2018) Sensitivity of hurricane intensity and structure to two types of planetary boundary layer parameterization schemes in idealized HWRF simulations. Trop Cyclone Res Rev 7:201–211. https://doi.org/10.6057/2018TCRR04.01

Thodsan T, Wu F, Torsri K et al (2021) Satellite radiance data assimilation using the WRF-3DVAR system for tropical storm Dianmu (2021) forecasts. Atmosphere 13:956. https://doi.org/10.3390/atmos13060956

Tiwari G, Kumar P (2022) Predictive skill comparative assessment of WRF 4DVar and 3DVar data assimilation: an Indian Ocean tropical cyclone case study. Atmos Res 277:106288. https://doi.org/10.1016/j.atmosres.2022.106288

Verma S, Panda J, Rath SS (2021) Role of PBL and Microphysical parameterizations during WRF simulated Monsoonal Heavy Rainfall episodes over Mumbai. Pure Appl Geophys 178:3673–3702. https://doi.org/10.1007/s00024-021-02813-z

Verma S, Kumar S, Kant S, Mehta S (2023) Sensitivity analysis of convective and PBL parameterization schemes for Luban and Titli tropical cyclones. Theoret Appl Climatol 151:311–327. https://doi.org/10.1007/s00704-022-04264-5

Vijaya Kumari K, Karuna Sagar S, Viswanadhapalli Y et al (2019) Role of Planetary Boundary layer processes in the Simulation of Tropical cyclones over the Bay of Bengal. Pure Appl Geophys 176:951–977. https://doi.org/10.1007/s00024-018-2017-4

Vishwakarma V, Pattnaik S (2021) Role of large-scale and microphysical precipitation efficiency on rainfall characteristics of tropical cyclones over the Bay of Bengal. Nat Hazards 114:1585–1608. https://doi.org/10.1007/s11069-022-05439-z

Vissa NK, Anandh PC, Gulakaram VS, Konda G (2021) Role and response of ocean–atmosphere interactions during Amphan

(2020) super cyclone. Acta Geophys 69:1997–2010. https://doi.org/10.1007/s11600-021-00671-w

Wang YQ, Wu CC (2004) Current understanding of tropical cyclone structure and intensity changes–a review. Meteorol Atmos Phys. https://doi.org/10.1007/s00703-003-0055-6. 87:257–78

Wu CC, Lien GY, Chen JH, Zhang F (2010) Assimilation of Tropical Cyclone Track and structure based on the Ensemble Kalman Filter (EnKF). J Atmos Sci 67:3806–3822. https://doi.org/10.1175/2010JAS3444.1

Wu C, Tu W, Pun I et al (2016) Tropical cyclone-ocean interaction in Typhoon Megi (2010)—A synergy study based on ITOP observations and atmosphere-ocean coupled model simulations. J Geophys Research: Atmos 121:153–167. https://doi.org/10.1002/2015JD024198

Xu H, Wang Y (2021) Sensitivity of fine-scale structure in Tropical Cyclone Boundary Layer to Model Horizontal Resolution at Sub-kilometer Grid Spacing. Front Earth Sci 9:707274. https://doi.org/10.3389/feart.2021.707274

Ye L, Li Y, Gao Z (2022) Evaluation of air–sea flux parameterization for Typhoon Mangkhut Simulation during Intensification Period. Atmos (Basel) 13:2133. https://doi.org/10.3390/atmos13122133

Yesubabu V, Kattamanchi VK, Vissa NK et al (2020) Impact of ocean mixed-layer depth initialization on the simulation of tropical cyclones over the Bay of Bengal using the WRF-ARW model. Meteorol Appl 27:e1862. https://doi.org/10.1002/met.1862

Zhang H, He H, Zhang WZ, Tian D (2021) Upper ocean response to tropical cyclones: a review. Geosci Lett 8:1–12. https://doi.org/10.1186/s40562-020-00170-8

Zhu T, Zhang DL (2006) The impact of the storm-induced SST cooling on hurricane intensity. Adv Atmos Sci 23:14–22. https://doi.org/10.1007/s00376-006-0002-9

Zi-Qian W, An-Min D (2012) A New Ocean mixed-layer model coupled into WRF. Atmospheric Ocean Sci Lett 5:170–175. https://doi.org/10.1080/16742834.2012.11446988