

Numerical simulation of tropical cyclone thane: role of boundary layer and surface drag parameterization schemes

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Abstract In the recent times, several advanced numerical models are utilized for the prediction of the intensity, track and landfall time of a cyclone. Still there are number of issues concerning their prediction and the limitation of numerical models in addressing those issues. The most pertinent question is how intensive a cyclone can become before it makes a landfall and where the cyclone moves under the ambient large-scale flow. In this paper, detailed study has been carried out using Weather Research Forecast model with two boundary schemes to address the above question by considering a recent tropical cyclone in Bay of Bengal region of North Indian Ocean. In addition, the impact of the surface drag effect on the low-level winds and the intensity of the cyclone are also studied. The result reveals that large differences are noted in the ocean surface fluxes between YSU and MYJ with MYJ producing relatively higher fluxes than YSU. It is found that the YSU scheme produced a better simulation for the THANE cyclone in terms of winds, pressure distribution and cloud fractions. Comparison with available observations indicated the characteristics of horizontal divergence, vorticity and vector track positions produced by YSU experiment are more realistic than with MYJ and other experiments. However, when the drag coefficient is changed as 0.5 or 2.0 from the default values, appreciable changes in the surface fluxes are not noticed. A maximum precipitation is reported in YSU as compared to the MYJ PBL scheme for the tropical cyclone THANE.

Keywords Tropical cyclone · Surface drag coefficient · Boundary layer · Track error · Model experiments

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1 Introduction

Tropical cyclones are one of the most natural disasters and interesting tropical atmospheric phenomena. It belongs to the class of extreme weather events that cause enormous damage along the coastal regions at the location of landfall due to strong winds, widespread and heavy rainfall activity as well as the storm surges (Bengtsson 2001). The Bay of Bengal (BOB) of the North Indian Ocean (NIO) is highly prone to tropical cyclones in the post-monsoon season (Neumann 1993) due to favorable environmental factors such as warm ocean waters ($SST \geq 26.5$ °C), weak vertical wind shear and convective instability. In the recent times, several advanced numerical models are used for the prediction of track and intensity of a cyclone. (e.g., Greeshma et al. 2015; Yeh et al. 2012; Zhang et al. 2011; Raju et al. 2011, 2012; Srinivas et al. 2013; Gopalakrishnan et al. 2012; Yesubabu et al. 2013). However, there are number of issues concerning their prediction and the limitation of numerical models in addressing those issues. The most pertinent questions are how intensive a cyclone can become before it makes a landfall? Where the cyclone moves under the ambient large-scale flow and the other environmental conditions?

Model physics is one of the issues that determine the prediction of the cyclones using numerical models. Among the various physical processes, the planetary boundary layer (PBL) and cumulus convection play significant role in the formation and intensification of cyclonic circulation by upward transfer of energy acquired from ocean source and its redistribution in the atmosphere. The PBL controls the vertical exchange of heat and moisture from the higher regions of the atmosphere through surface drag effects and subsequent turbulent diffusion processes (Gopalakrishnan et al. 2012). These transport and diffusive processes are represented through sub-grid scale parameterization schemes in atmospheric models as they cannot be fully resolved even at the highest possible resolution at the present times. The PBL diffusion processes are parameterized based on different concepts or hypothesis and influence the forecasts. The PBL schemes essentially are dependent on various crucial parameters such as surface exchange coefficients for momentum (C_d), surface exchange moisture and heat (C_k), eddy diffusivity for momentum (K_m) and eddy diffusivity of moisture and heat (K_h). These coefficients are estimated from the land–surface/ocean to the atmosphere through the transfer and diffusion of fluxes and vice versa. However, there is a large extent of uncertainty in the estimates of these parameters. Consequently, the surface and planetary boundary layer parameterization schemes used in the mesoscale models are sensitive in prediction of TC structure, track and intensity (Nolan et al. 2009a, b). Braun and Tao (2000) demonstrated that the track prediction controlled by cumulus schemes whereas intensity of TC influenced by PBL schemes. The horizontal resolution is important in simulating cyclone intensity as finer grid resolution produces the stronger convergences and vertical velocity (Rao et al. 2009; Kanase and Salvekar 2014; Li and Pu 2008). With the advancement in our understanding together with our increased ability to observe the atmospheric systems, it has now become possible to develop better turbulence models within the atmospheric models. In this paper, a very severe cyclone THANE formed over Bay of Bengal during December 25–31, 2011, is considered for investigating the sensitivity of the boundary layer schemes on track and intensity prediction of cyclone. Also, the impact of the surface drag effect on the low-level winds and the intensity of the tropical cyclone studied through numerical experiments. A brief description of THANE cyclone is provided in Sect. 2. Model and experimental design is given in Sect. 3. Sect. 4 discusses the results of the study and followed by conclusions in Sect. 5.

2 Brief description of THANE cyclone

A depression formed over southeast Bay of Bengal on December 25 2011 and moved to north-northwestwards and strengthened into a deep depression at 0000 UTC of December 26. The system further increased its strength and became a cyclonic storm named 'THANE' at 1200 UTC of December 26. The cyclone THANE moved west-northwestwards and intensified into a severe to very severe cyclonic storm between 0600 UTC and 1200 UTC of December 28. Thereafter, it moved west-southwestwards and crossed between Cuddalore and Puducherry on 0200 UTC of December 30, 2011, with a maximum wind of 120–140 km h⁻¹. The system rapidly weakened into a deep depression at 0900 UTC of December 30 over north coastal Tamil Nadu and into a depression at 12 UTC of December 30 over the north interior Tamil Nadu. Cyclone THANE has been categorized as a very severe cyclone. At the time of cyclone landfall, a maximum wind speed of about 37.5 ms⁻¹ and heavy rainfall reported which caused a severe damage of property between Puducherry and Cuddalore districts of Tamil Nadu.

3 Atmospheric model and experimental design

The Advanced Weather Research Forecast (WRF) model version 3.4 is used in this study for simulation of the characteristics of the tropical cyclone. The model has Eulerian mass dynamical core (WRF-ARW) developed by NCAR (Klemp et al. 2008). The WRF model is non-hydrostatic mesoscale model suitable for high-resolution simulation/prediction of high impact weather events. The model equation consists of prognostic variables of three-dimensional wind, perturbation quantities of potential temperature, geopotential, surface pressure, turbulent kinetic energy and scalars (water vapor mixing ratio, cloud water etc.). The model uses Arakawa C-grid staggered horizontally and vertical coordinate with terrain following hydrostatic pressure levels. The time integration schemes of third-order Runge–Kutta method are used in the model (Michalakes et al. 2005). The model has various options for spatial discretization, diffusion, nesting, lateral boundary forcings and physical parameterization schemes.

In this study, the WRF model is designed as three nested grid domains of horizontal grids of 27, 9, 3 km with two-way interactive way so that the information shared mutually between the domains. Four numerical experiments are conducted to study the important features of the tropical cyclone THANE. These experiments are different in respect of the PBL turbulence parameterization and the surface drag coefficients. In all experiments, the model is started at 0000 UTC of December 28, 2011, and integrated for 60 h, i.e., up to 1200 UTC December 30, 2011. The geophysical information such as terrain height, land use and soil category data is taken from USGS at a resolution of arc 30 s, and the data are interpolated to all the model grids. The three-dimensional meteorological data for the initial conditions and 6-hourly time varying boundary conditions for the outer domains are derived from 0.5-degree analysis data of National Centers for Environmental Prediction (NCEP), USA. The SST data are also taken from the same source. The model physics included WRF single-moment 6-class scheme microphysics, a scheme which includes ice, snow and graupel processes suitable for high-resolution simulations. RRTM scheme for long-wave radiation, Dudhia scheme for shortwave radiation (Dudhia 1989); MM5-Monin–Obukhov similarity theory for surface layer, NOAA land surface model (Chen and Dudhia 2001); two boundary layer schemes such as Mellor–Yamada–Janjic (MYJ) scheme (Janjic 1994); and

Yonsei State University (YSU) non-local diffusion scheme (Hong et al. 2006); Kain–Fritsch convection scheme are used in this study. The detailed model configuration and physical schemes used in this study are given in Table 1. In the MYJ PBL scheme, the eddy diffusivity coefficient is derived from the turbulence kinetic energy, whereas the YSU scheme treats the diffusivity using K-theory and the counter-gradient fluxes due to large convective eddies in the PBL. Within each PBL scheme, the surface fluxes are computed using a similarity scheme wherein the surface drag coefficients are used. The different experiments are named as (1) YSU (with PBL physics as YSU scheme), (2) MYJ (with PBL physics as MYJ scheme), (3) MYJ-0.5 (with PBL as MYJ scheme and drag coefficient C_d as 0.5 times the default values) and (4) MYJ-2.0 (with PBL as MYJ scheme and drag coefficient C_d as 2.0 times the default values).

4 Results and discussion

4.1 Temporal variation of mean sea level pressure and wind

The time variation in central sea level pressure (CSLP) and maximum surface winds (MSW) from experiments MYJ, YSU, MYJ-0.5, MYJ-2.0 along with IMD estimates is shown in Fig. 1. It is seen from Fig. 1a that the pressure variation in the simulation YSU is relatively higher than that in MYJ indicating a stronger cyclone in YSU compared to MYJ. The IMD estimates depict a maximum pressure drop in comparison with both YSU and MYJ simulations. These variations are perhaps related to differences in the exchange coefficients in YSU and MYJ. The pressure variation in the experiments MYJ-0.5 and MYJ-2.0 is nearly equal to MYJ giving slightly higher pressure drop than MYJ-0.5 experiment. Comparison of pressure variation in all the experiments shows the MYJ produces the maximum pressure drop followed by MYJ-0.5. This suggests an increase in the drag coefficient leads to weaken the cyclone by increasing the pressure.

Table 1 Model configuration

Dynamics	Primitive equation, non-hydrostatic		
Vertical resolution	45 vertical levels	45 vertical levels	45 vertical levels
Domains	Domain 1	Domain 2	Domain 3
Horizontal resolution	27 km	9 km	3 km
Grid points	130 × 130	226 × 226	454 × 400
Domains	1.9613°N–35.3688°N 64.7626°E–100.9374°E	5.4122°N–25.3064°N 72.8949°E–93.9267°E	7.8879°N–19.9013°N 77.1012°E–91.2160°E
Initial/boundary conditions	NCEP GFS analysis/forecasts at 6-h interval		
Radiation	Dudhia scheme for shortwave and RRTM for long-wave processes		
Convection	Kain–Fritsch 2		
PBL turbulence	YSU—non-local scheme Mellor–Yamada–Janjic TKE closure		
Microphysics	WRF single-moment 6-class scheme		
SOIL model	Multi-layer soil thermal diffusion scheme		
SST	Time varying SST from NCEP GFS data		

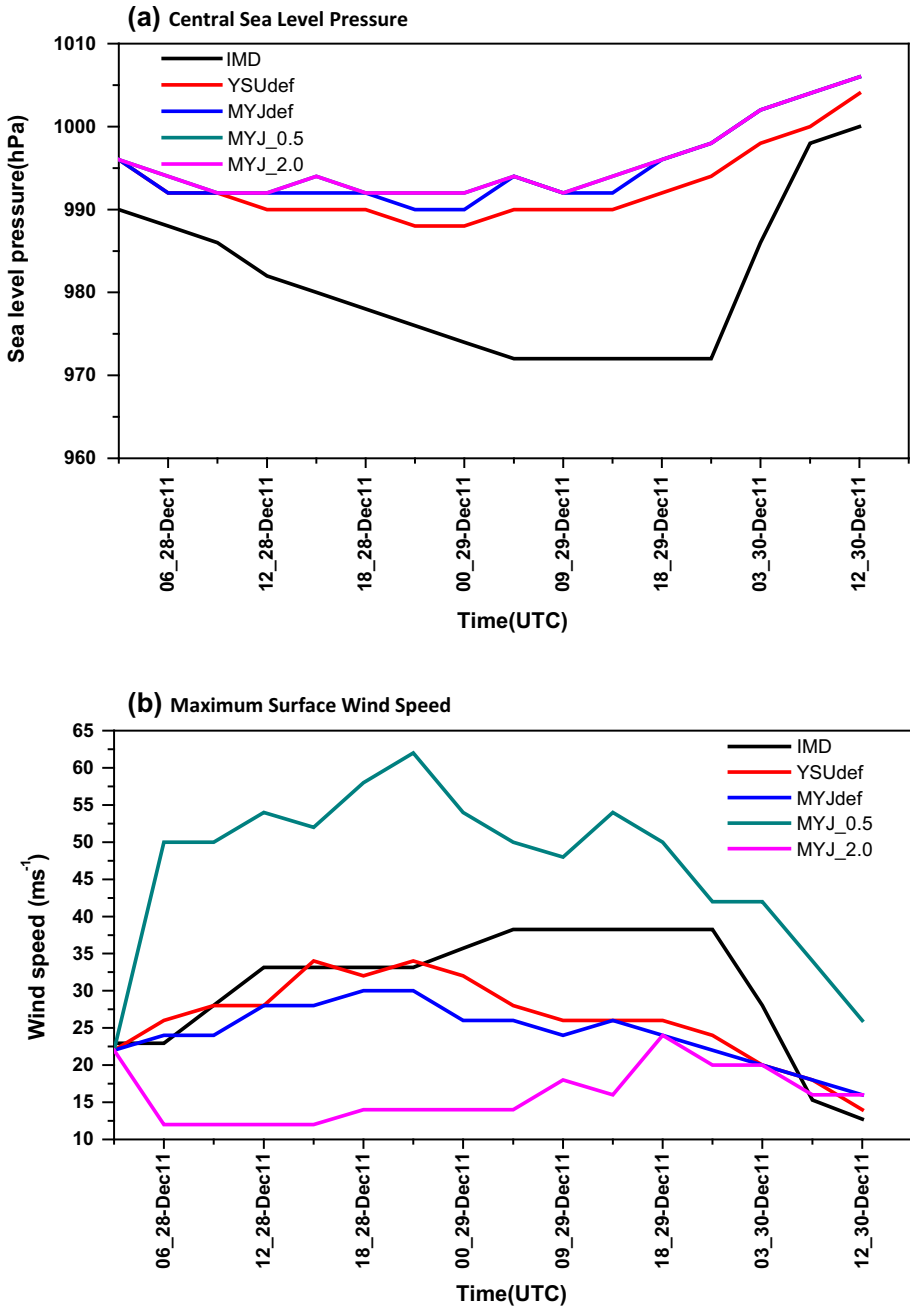


Fig. 1 Time variation of **a** central sea level pressure, **b** maximum surface wind speed in different PBL experiments

The time variation in maximum tangential winds (Fig. 1b) shows the highest winds are found with YSU followed by the MYJ in the control runs indicating a stronger cyclone in YSU compared to MYJ. In the experiments using MYJ and changing the drag coefficients,

MYJ-0.5 produces the strongest winds followed by MYJ and MYJ-2.0. This shows the reduced drag coefficient (0.5 C_d) leads to higher low-level winds in MYJ-0.5 than in the experiment MYJ-2.0 four times higher drag coefficient in the experiment MYJ-0.5. From these experiments, it is evident that the drag effect is to reduce the winds (both the tangential and radial components). This is more clearly seen in the azimuthally averaged wind diagrams described below.

4.2 Azimuthally averaged tangential winds

The azimuthally averaged winds (i.e., radius-height cross section of winds) around the core of the cyclone from the four simulations are illustrated in Fig. 2. The top panel shows the azimuthally averaged winds from YSU, MYJ schemes and the bottom panel depicts MYJ-0.5 and MYJ-2.0, respectively. The radial and vertical distributions show that among the different experiments the maximum radial winds are produced in YSU scheme followed MYJ_0.5, MYJ

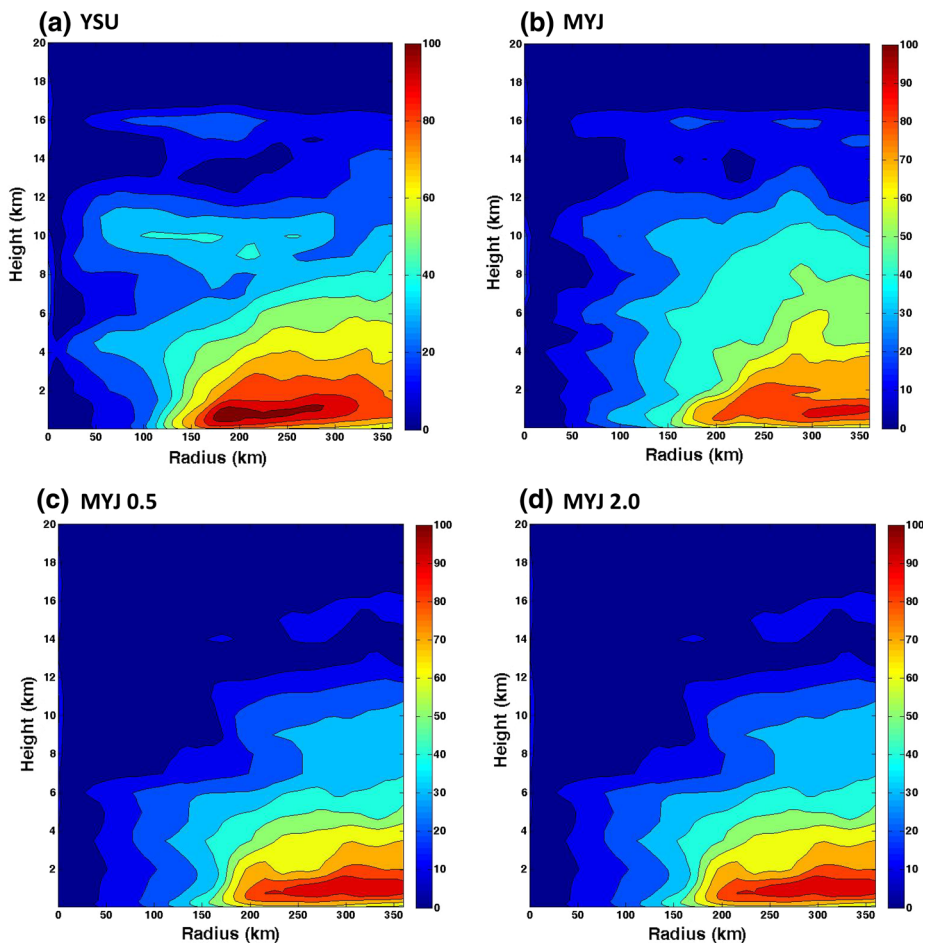


Fig. 2 Azimuthally averaged tangential winds of THANE cyclone in the experiments for **a** YSU, **b** MYJ, **c** MYJ-0.5 and **d** MYJ-2.0

and MYJ_2.0, respectively. The effect of reduced drag coefficient is to increase the radial winds in the inflow region. The azimuthal wind plots from MYJ, MYJ_0.5, MYJ_2.0 experiments (Fig. 2b–d) suggest that alteration in the surface drag coefficient influences the winds vertically up to 10 km region and the effect reduces drastically in the layer above 10 km.

4.3 Azimuthally averaged temperature anomaly

The azimuthally averaged temperature anomaly (i.e., the deviation of cyclone temperature from normal atmospheric temperature before cyclone formed) is shown in Fig. 3. The maximum temperature anomaly is noted in the layer between 4 to 8 km region and radially to 225 km from the center of the cyclone. The maximum temperature anomaly is noticed in MYJ (~6 K) followed by MYJ-0.5 (~4 K), MYJ-2.0 (~3.5 K) and YSU (~2.0 K). Among the control experiments, the MYJ shows higher warming compared to YSU. These results suggest that the turbulent drag can influence the thermodynamical structure of the storm through low-level winds (dynamics) and coupling between the dynamical and thermodynamical processes such as convergence, convection, mixing. The lower drag (i.e. $C_d = 0.5 C_d$) leads to a higher warming than the control simulation. The reduced drag (0.5 C_d) would increase the winds in the inflow

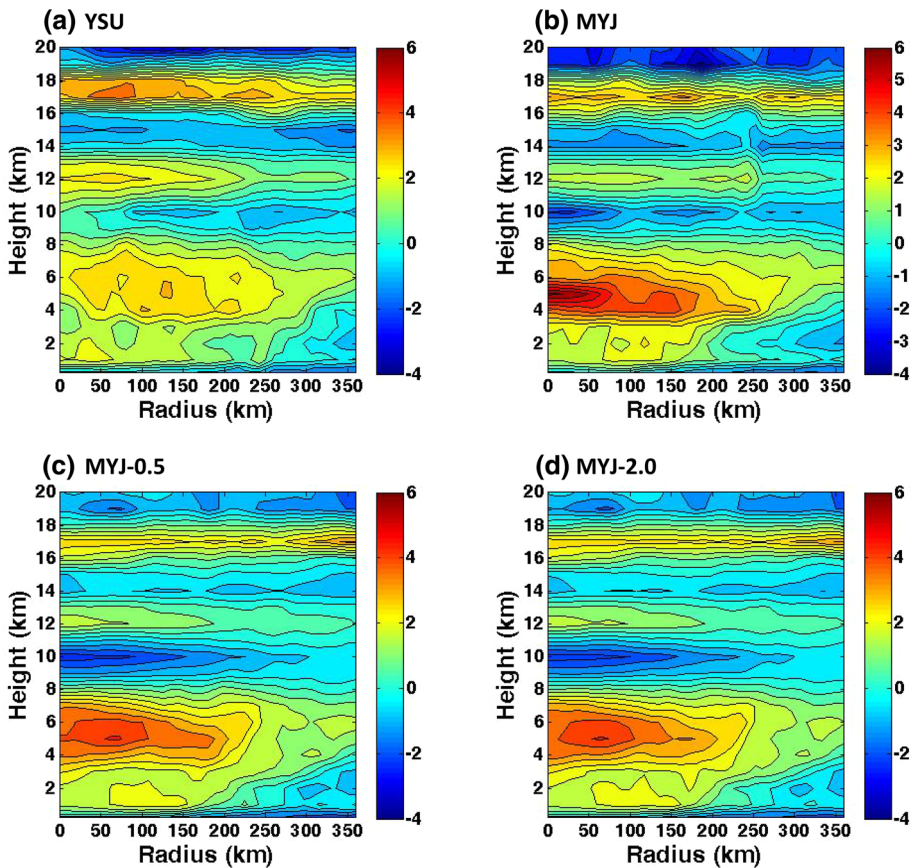


Fig. 3 Azimuthally averaged temperature anomaly of THANE cyclone in the experiments for **a** YSU **b** MYJ **c** MYJ-0.5 and **d** MYJ-2.0

region, facilitating stronger low-level convergence and thus leading to higher convection, ultimately leading to larger warming in the upper layers.

The stronger convection related to reduced drag effect is analyzed from vertical winds. Radial height cross section of azimuthally averaged vertical winds in the four experiments is presented in Fig. 4. It is seen that the vertical winds in the lower regions (<4.0 km region) are stronger in the YSU followed by MYJ, MYJ-0.5 and MYJ-2.0 experiments. However, the vertical winds in the upper regions (10–14 km) are stronger in the experiment MYJ than the rest. The vertical winds may be related to the convergence of radial winds and associated convection, which is differently simulated with different surface drag coefficients. Obviously, YSU PBL scheme simulates highest radial velocities thereby producing a higher vertical wind in comparison with the other experiments. In the simulations using MYJ, the reduced surface drag coefficient (0.5 Cd) increased the radial winds, low-level convergence thus leading to higher convection and warming in the upper atmosphere compared to both MYJ and MYJ-2.0.

4.4 Vertical cross section

4.4.1 Tangential winds

The vertical section of tangential winds at the highest intensive stage of the cyclone (2100 UTC December 28, 2011) is plotted from the four numerical experiments in Fig. 5. The

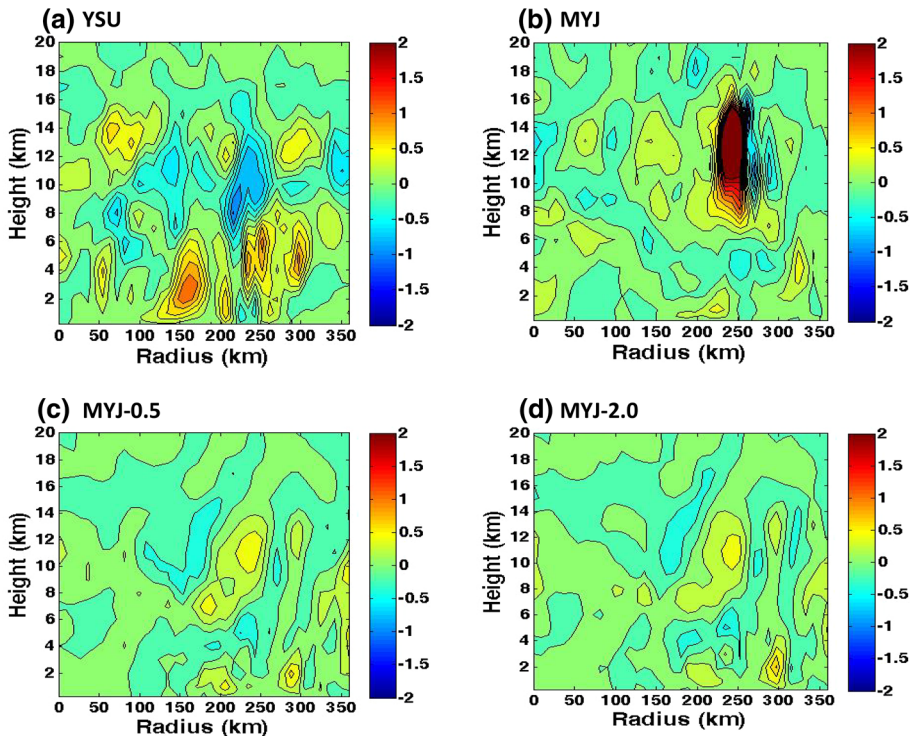


Fig. 4 Azimuthally averaged vertical winds around the cyclone for **a** YSU, **b** MYJ, **c** MYJ_0.5 and **d** MYJ_2.0 experiments

vertical section is drawn at latitude 12.27°N. It is seen that the tangential winds are stronger in the case YSU up to 500 hPa compared to MYJ, MYJ-0.5 and MYJ-2.0 experiments. MYJ-2.0 produced the lowest tangential winds than the other three experiments which is due to increase in friction by higher surface drag effect. It is observed that in the inner core region of the cyclone the wind increased in the case MYJ-0.5 and decreased in the case MYJ-2.0 as compared to the MYJ scheme. Overall the tangential winds up to 400 hPa level are influenced by changes in the drag coefficient values. In YSU, it is observed that the maximum wind intensity is located in the western sectors of the cyclone core that is more prominently seen in YSU and MYJ-0.5. In the inner core region, the wind intensity extending up to 2 km with a maximum of about 38 ms⁻¹ in YSU and 32 ms⁻¹ in MYJ schemes.

4.5 Radial winds

The radius-height cross section of meridional winds at the mature stage of the cyclone at 12.27°N from different experiments is shown in Fig. 6. This shows the radial winds are stronger in the YSU and MYJ experiments. In the inner core region, the radial winds increased in the experiments using MYJ with reduced drag coefficient (0.5 Cd). This change in surface radial winds is associated with reduction in radial winds in the outflow

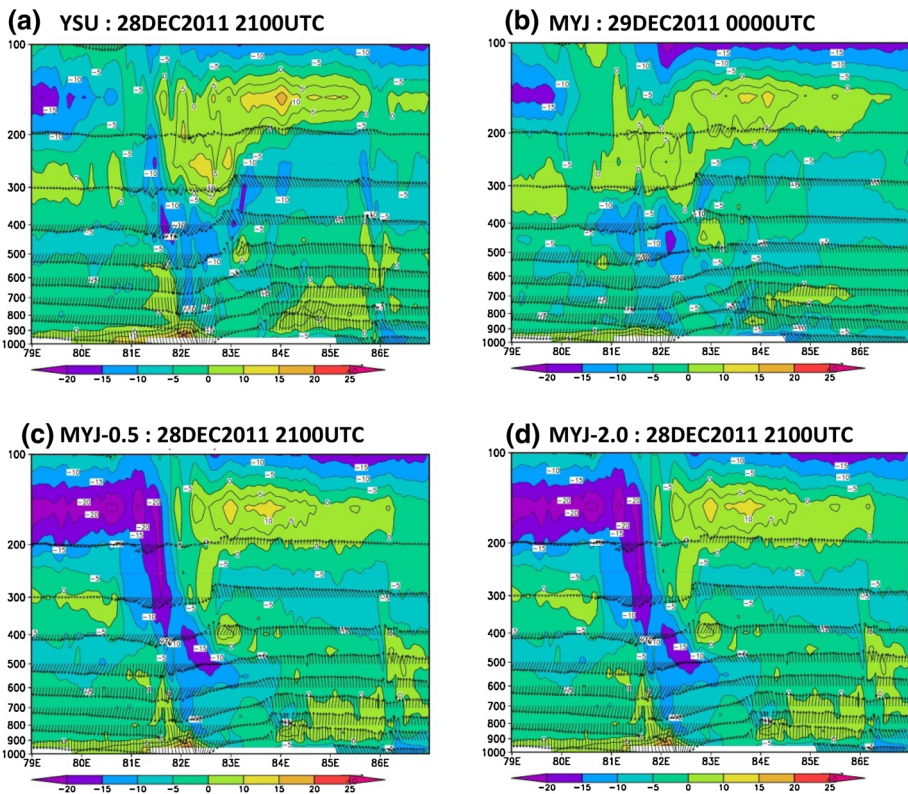


Fig. 5 Vertical cross section of tangential winds (ms⁻¹) at cyclone intensified period with different numerical experiments for **a** YSU, **b** MYJ, **c** MYJ-0.5 and **d** MYJ-2.0

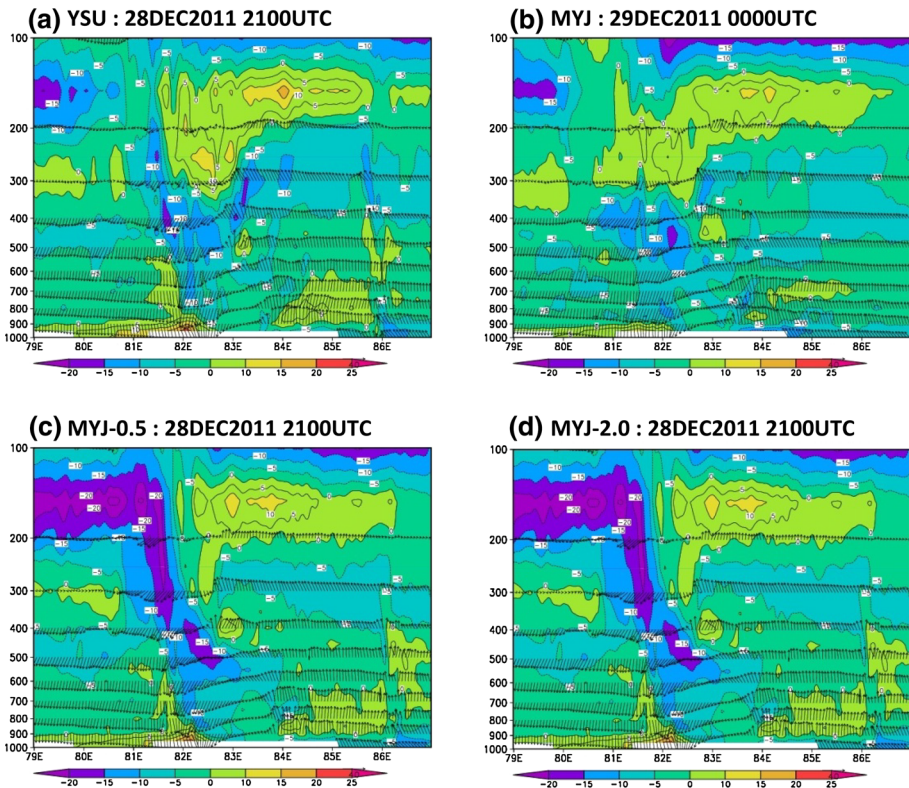


Fig. 6 Vertical cross section of radial winds (ms^{-1}) at cyclone intensified period with different numerical experiments for **a** YSU, **b** MYJ, **c** MYJ-0.5 and **d** MYJ-2.0

region. The radius-height cross section of zonal winds at the mature stage of the cyclone at 12.27°N is shown in Fig. 6. As in the case of azimuthally averaged tangential winds (Fig. 2) experiment, YSU produced stronger tangential winds as compared to MYJ. In the experiments with changing the drag coefficient values, the experiment MYJ-0.5 produced stronger tangential winds than MYJ. The change in C_d (0.5 C_d) also led to reduction in the strength of outflow at 150 hPa level (Fig. 7).

4.6 Surface fluxes

The variation in the surface drag or enthalpy coefficient (C_d/C_k) can lead to changes in the surface fluxes emitted from the ocean surface. The time series of the heat flux averaged over area of $2^\circ \times 2^\circ$ grid around the cyclone is depicted in Fig. 8. The differences in the sensible heat fluxes among the different experiments are meager in the developing stages. However, large differences are seen in the ocean surface fluxes between YSU and MYJ with MYJ giving higher fluxes than YSU during the highly intensified stage of the cyclone (1200 UTC December 29). Small differences in the sensible heat fluxes are noted when the drag coefficient is varied as 0.5 or 2.0 from the default values. In the present simulations the value of C_d alone is changed and C_k is kept the default value. It is obvious that C_k will have higher influence on surface fluxes than C_d .

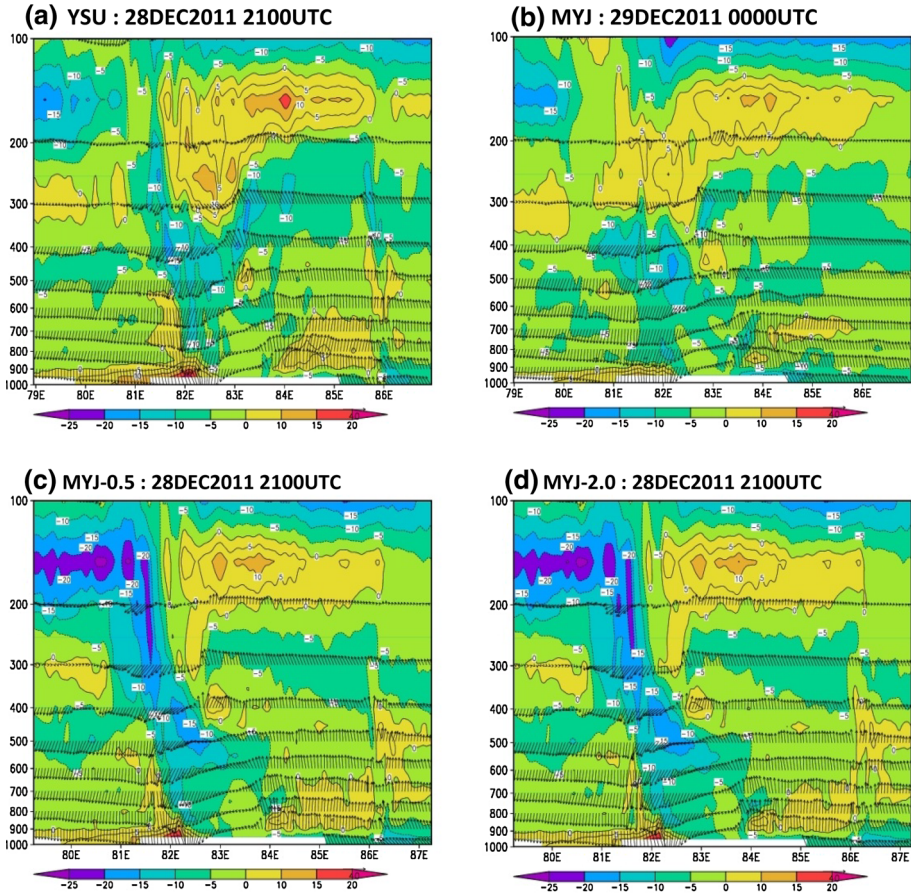


Fig. 7 Vertical cross section of zonal winds (ms^{-1}) at cyclone intensified period with different numerical experiments for **a** YSU, **b** MYJ, **c** MYJ-0.5 and **d** MYJ-2.0

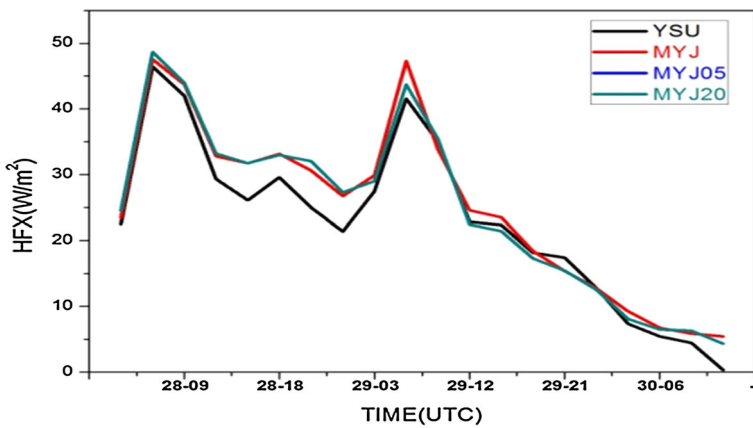


Fig. 8 Time series of sensible heat flux (Wm^{-2}) with different PBL schemes

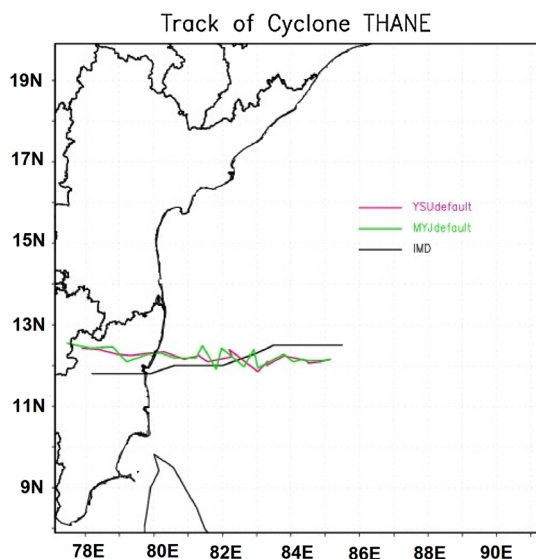
4.7 Vector track and track error

The vector track positions of the THANE cyclone from simulations of MYJ, YSU and IMD estimated best track are depicted in Fig. 9. Both the simulations produced similar movement of the cyclone with almost similar vector track errors as compared to the IMD estimated track. However, the MYJ gives a wavy nature (random movement) of the cyclone, whereas the YSU produced nearly a linear motion. The track errors are about 60 km in the initial stages, reduce to 30–25 km and then increase to 90 km in both the experiments. When the drag coefficient is changed to 0.5 or 2.0, the track error slightly reduced by 10% in the initial stages and then slightly increased by about 10% (Fig. 10). These differences in cyclone track are negligible with different drag coefficients when compared to change in the MYJ PBL scheme. The landfall position error is slightly more in MYJ compared to YSU PBL scheme.

4.8 Divergence and vorticity

Considering various parameters of circulation pattern, pressure, cloud fractions, track position, the YSU boundary scheme in WRF model is most appropriate and suitable PBL schemes in simulation for the THANE cyclone. In this section, we further analyzed divergence and vorticity during the intensive stage of cyclone. The horizontal divergence at 925, 850, 500 and 200 hPa levels in the simulation YSU at the intensive stage of THANE corresponding to 21 UTC December 28, 2011, is shown in Fig. 11. This plot essentially describes the low-level convergence and upper-level divergence pattern for the THANE cyclone. The outer core region of the cyclone depicts strong convergence bands ($-60.0 \times 10^{-5} \text{ s}^{-1}$) in the forward right sectors at the lower regions (925 hPa) with progressively decreasing convergence. The convergence reduced to $-30 \times 10^{-5} \text{ s}^{-1}$ at 850 hPa level and further reduced to $-10.0 \times 10^{-5} \text{ s}^{-1}$ at 500 hPa level. In the upper atmosphere, strong divergence ($\sim 20.0 \times 10^{-5} \text{ s}^{-1}$) is found at 200 hPa indicating upper-

Fig. 9 Simulated tracks of the THANE cyclone with different PBL experiments of MYJ, MYJ-0.5 and MYJ-2.0



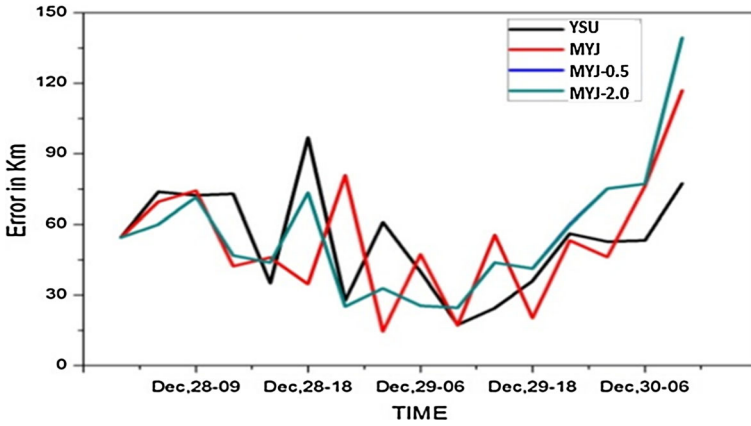


Fig. 10 Vector track errors of THANE from different numerical experiments (MYJ-0.5 and MYJ-2.0 are overlapped with one another)

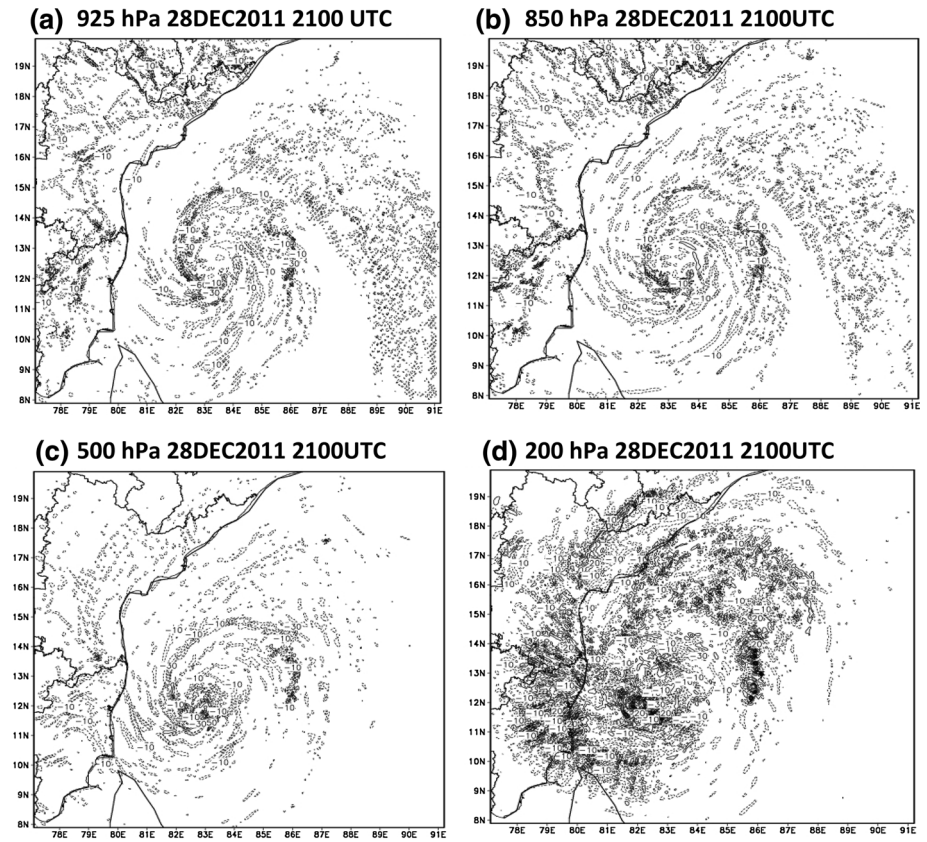


Fig. 11 Horizontal divergence associated with THANE cyclone at **a** 925 hPa, **b** 850 hPa, **c** 500 hPa and **d** 200 hPa levels

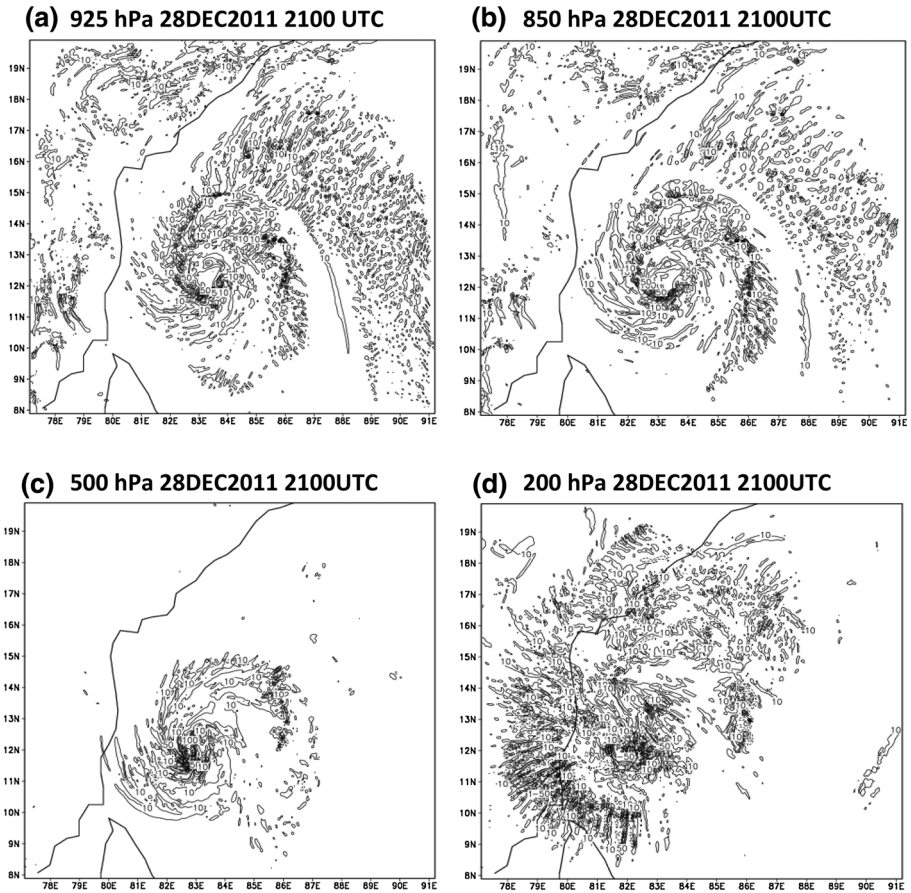


Fig. 12 Vorticity associated with THANE cyclone at **a** 925 hPa, **b** 850 hPa, **c** 500 hPa and **d** 200 hPa

level outflow. The strongest outflow is located directly above the core of the low-level cyclone and with progressively decreasing divergence in the outer sectors.

The vorticity distribution during intensive stage of the cyclone corresponding to 2100 UTC on December 28, 2011, at 925, 850, 500 and 200 hPa is illustrated in Fig. 12. The cyclonic circulation (positive vorticity) is noticed in the lower levels, and negative vorticity (anticyclonic circulation) is simulated in the upper atmosphere. The highest cyclonic vorticity ($\sim 100.0 \times 10^{-5} \text{ s}^{-1}$) is observed in the inner core region and its forward right sectors and indicates a symmetric distribution of vorticity around the low-level vortex. The positive vorticity gradually decreased aloft. In the upper atmosphere (200 hPa), anticyclonic vorticity distribution is noticed with maximum values of $-10.0 \times 10^{-5} \text{ s}^{-1}$. This indicates the weakening of vortex at the middle and upper regions of the cyclone.

4.9 Rainfall

The 24-h accumulated rainfall for day1 (top panel), day2 (middle panel) and day3 (bottom panel) forecast of four experiments and the corresponding TRMM estimates (Huffman

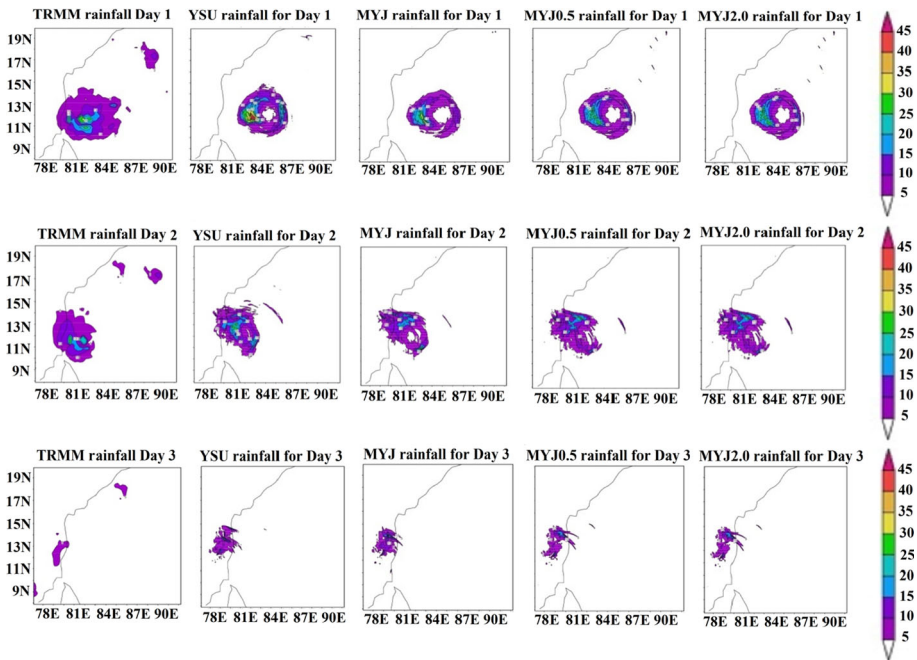


Fig. 13 Rainfall for day1 (top panel), day2 (middle panel) and day3 (bottom panel) with TRMM estimates and different PBL experiments of YSU, MYJ, MYJ-0.5 and MYJ-2.0

et al. 2007) are depicted in Fig. 13. The spatial distribution of precipitation is well simulated in all four experiments as compared with TRMM estimates; however, some differences are noticed in terms of intensity. In day1 forecast (top panel), the precipitation is overestimated in the YSU scheme with a maximum of 45 cm day^{-1} against TRMM estimation (30 cm day^{-1}). The simulation with YSU scheme delineates more wet bias than other three experiments. In day2 forecast (middle panel), the precipitation reported by all experiments is comparable to the TRMM estimates; however, it is slightly overestimated in YSU experiment (20 cm day^{-1}), but in remaining experiments, the precipitation is noticed 15 cm day^{-1} . The rainfall in day3 forecast for the four experiments and corresponding TRMM estimates (Fig. 13c) reveals that in all experiments the precipitation is overestimated as compared to the TRMM estimates.

5 Conclusions

The influence of the PBL turbulence parameterization schemes and surface drag effect on the tropical cyclone simulation was investigated using WRF modeling system. The PBL and surface layer parameterizations are influential in the numerical simulations due to the drag and diffusivity effects which are variously parameterized by various schemes. While the diffusivities enhance or weaken the momentum, heat in the PBL and outer atmospheric regions, the drag coefficients for heat/momentum (C_d, C_k) essentially regulate the surface momentum and enthalpy fluxes in the inflow region thereby control the overall dynamics of a tropical cyclone. These effects have been extensively studied by various research

groups in the development of suitable surface and PBL schemes for tropical cyclone forecasting. In the present study, two PBL schemes (YSU non-local scheme and MYJ TKE scheme) are employed for this objective. The exchange coefficients in YSU scheme are calculated using a first-order relationship and the counter-gradient fluxes. In the MYJ scheme, the exchange coefficients are estimated from the turbulence kinetic energy and a master length scale. The numerical experiments conducted with the YSU non-local diffusion scheme and the MYJ TKE closure higher-order scheme indicated considerable variation in the low-level maximum tangential winds, central pressure and their time evolution associated with the cyclone. The YSU produced maximum pressure drop, and stronger tangential winds as compared to the MYJ experiment. When the surface drag coefficients are changed from default model values to 0.5 and 2.0 in the MYJ PBL scheme, it was found that the pressure drop is relatively higher and winds are stronger with $C_d = 0.5 C_d$. The effect of reduction in the drag coefficient is to reduce the winds in the cyclone. This is more clearly seen in the azimuthally averaged parameters such as winds, temperature anomaly and vertical winds around the core of the cyclone. Essentially the radial winds enhanced in the inflow region leading to higher convergence, more vertical motion and higher warming as compared to the default MYJ case. Large differences are noted in the ocean surface fluxes between YSU and MYJ with MYJ producing relatively higher fluxes than YSU. However, when the drag coefficient is changed as 0.5 or 2.0 from the default values, appreciable changes in the surface fluxes are not noticed which may be due to the same C_k value used in all the experiments where C_d is changed.

While some considerable variation in the cyclone track is noticed with change in the PBL scheme, no perceivable variation is identified in the track simulated with change in the surface drag coefficient. Nevertheless, the YSU scheme tends to produce a better simulation for the THANE cyclone in terms of winds, pressure distribution and cloud fractions. Comparison with available observations indicated the characteristics of horizontal divergence, vorticity, winds, pressure and vector track positions produced by YSU experiment are more realistic than with MYJ and other experiments.

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