



A Qualitative study of Some Meteorological Features During tropical Cyclone PHET Using Satellite Observations and WRF Modeling System

Jagabandhu Panda · Harvir Singh · Pao K. Wang · R. K. Giri · Ashish Routray

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Abstract The satellite derived meteorological parameters are quite useful for understanding the genesis of a tropical cyclone. This paper analyses some of the characteristic features of the tropical cyclone (TC) PHET using satellite derived meteorological observations, and numerical model simulations while investigating the performance of various cumulus parameterization schemes using Weather Research and Forecasting (WRF) modeling system. The genesis of the TC is primarily discussed using the observed meteorological parameters including the outgoing long-wave radiation, quantitative precipitation estimate (or rainfall), sea surface temperature, relative vorticity and upper tropospheric humidity. These satellite derived parameters show suitable meteorological condition for the development and propagation of the TC. The qualitative analysis of WRF simulated results indicates that Kain-Fritsch cumulus scheme (Kain and Fritsch, 1990 and 1993; Kain, 2004) performs relatively better in predicting

various parameters in relation to the genesis and propagation of PHET.

Keywords WRF modeling system · Phet · Genesis · Tropical cyclone · Satellite observations · Quantitative precipitation estimate · Outgoing long-wave radiation · Relative vorticity

Introduction

The tropical cyclone (TC) hazards come mainly from high-speed winds and heavy rainfall, which often cause massive loss of lives and properties to the invaded countries, especially at the coastal areas. Therefore, a skilful forecast of TC activity in a particular basin is one of the top priorities within the scientific community in order to mitigate these losses. For instance, the loss of lives and property damages due to TCs in the west coast of India is ranked as the most important cause among all the natural disasters in this region (Joseph et al. 2011). Thus, the understanding of genesis and improvement in the forecasting skill for the TCs over Arabian Sea is quite a significant issue. The purpose of continuous efforts in analysing several cyclonic storms is to improve the forecasting techniques so that the early warnings could be issued and enhance physical understanding of several meteorological parameters in relation to the formation and movement of TCs. In view of this, the characteristic features of the tropical storm PHET are presented in this study using satellite measurements, and the simulated results from Weather Research and Forecasting (WRF) modeling system.

Analysing the satellite data products for any weather event is a complicated affair, since it requires appropriate techniques, proper methodology and algorithms or software (e. g. Jaishwal et al. 2012; Song et al. 2014). Significant amount of literature is available, which study weather events using satellite data (e. g. Deb et al. 2009; Giri et al. 2012; Jaishwal

J. Panda · P. K. Wang
Research Center for Environmental Changes, Academia Sinica,
Nankang, Taipei 11529, Taiwan

H. Singh · A. Routray
National Centre for Medium Range Weather Forecasting
(NCMRWF), Ministry of Earth Sciences, Noida, U. P, India

R. K. Giri
Regional Meteorological Centre, India Meteorological Department,
Patna, Bihar, India

P. K. Wang
Department of Atmospheric and Oceanic Sciences, University of
Wisconsin-Madison, 1225 W. Dayton Street, Madison, WI 53706,
USA

Present Address:

J. Panda (✉)
Department of Earth and Atmospheric Science,
National Institute of Technology Rourkela, Rourkela, Odisha, India
e-mail: jagabandhu@gmail.com

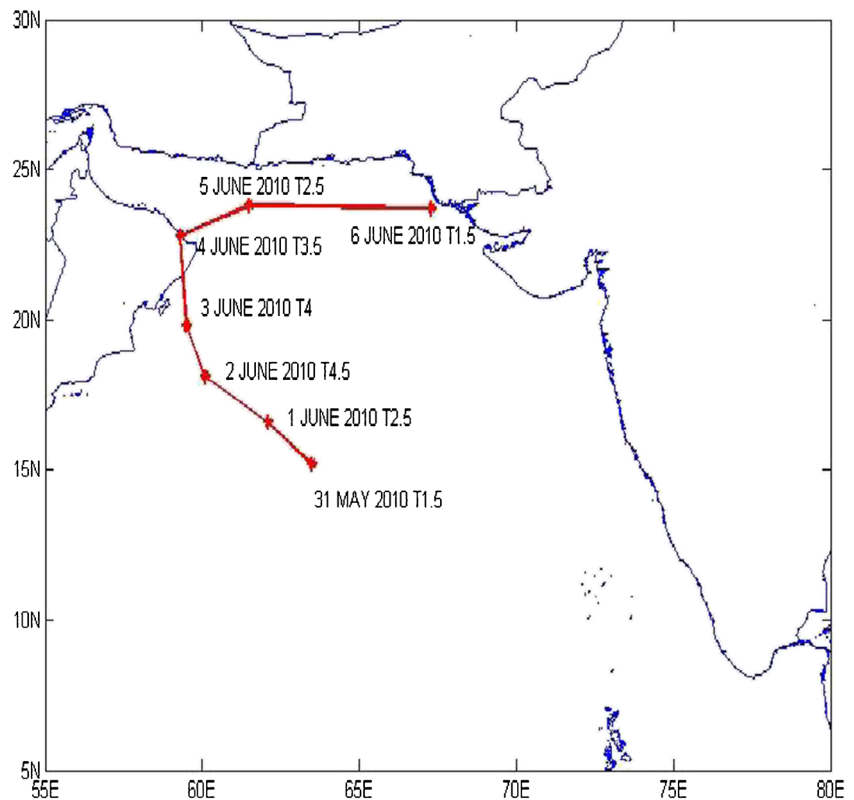
et al. 2012; Mitra et al. 2013; Panda et al. 2011; Panda and Giri 2012; Singh et al. 2008). For instance, the study of Singh et al. (2008) used Special Sensor Microwave Imager (SSM/I) and Quick Scatterometer (QuikSCAT) satellite observations in order to analyse and understand the impact on the simulation of the Orissa super cyclone (that occurred over the Bay of Bengal in October 1999) using the fifth-generation Pennsylvania State University–National Center for Atmospheric Research Mesoscale Model or MM5 (Grell et al. 1995). In another study based on historical Mumbai rainfall event (occurred on July 26, 2005), they also analysed the impact of atmospheric infrared sounder data from Aqua satellite (part of NASA's earth observation system) using MM5 model (Singh et al. 2008). Some of the earlier studies by Rakesh et al. (2009) and Vinodkumar et al. (2008) also used satellite measurements including QuikSCAT surface winds in order to study the characteristic features of Indian summer monsoon depression. Another study by Deb et al. (2011) assimilated the satellite measurements from INSAT for the simulation of the tropical cyclone AILA. However, the present study is an effort to utilise the satellite derived products and the WRF model simulations for analysing some meteorological features during the occurrence of tropical cyclone PHET. The observed features of the tropical cyclone are presented using various satellite derived measurements from MODIS, METEOSAT-7 and KALPANA-1 depending upon the availability of the data.

Observed history and Associated Meteorological Features

The tropical cyclonic storm PHET developed from a low pressure area formed over the central Arabian Sea on May 30, 2010. The cyclone had a special and rarely observed track (Fig. 1) in the history of records during 1877–2010 and was having one of the longest tracks in the recent years (RSMC 2011; Report on cyclonic disturbances over north Indian Ocean during, 2010). It affected three countries including India, Pakistan and Oman. The loss of life and property was significant in Oman and Pakistan due to heavy rain and wind. However, there was not much adverse effect in India.

According to IMD (India Meteorological Department) observation, there was a solid convective cloud cluster persisting over south-east adjoining east-central Arabian Sea for a considerable period of time on May 30, 2010. At 0600 UTC (on May 30), it was a low level circulation and at 1200 UTC it was observed as a vortex centered at 14.0°N/65.0°E with intensity T1.0. It remained stationary with the same intensity till 21 UTC. The low pressure area concentrated into a depression over the same region on May 31 and was observed to be moving (at 0000 UTC on May 31) in a north-westerly direction with unchanged intensity and center as 14.5°N/64.5°E (figure not shown for brevity). It maintained its slight westerly/north-westerly movement till 2100 UTC (on May 31) when its center was located at 15.2°N/63.5°E (figure not shown) and intensity as T1.5. At the center of the cyclone, the values of OLR

Fig. 1 Observed track of cyclone PHET (1200UTC). The x-axis indicates the longitudes (in degree) and y-axis indicates the latitudes (in degree)



(Outgoing Long-wave Radiation) are found to be minimum while the QPE (Quantitative Precipitation Estimate) was maximum. Accordingly, the journey of PHET can be depicted.

Initially the cyclonic system moved in north-westerly direction and intensified into a cyclonic storm on June 01. At 0000 UTC on June 01, the intensity of the tropical cyclone increased to T2.0. At 0600 UTC the center was at 15.8°N/

62.9°E and the signs of rapid intensification were observed at this hour. The intensity of the cyclonic storm increased to T2.5 at 0900 UTC (on June 01) with center at 16.3°N/62.7°E. At 1200 UTC on June 01, the tropical cyclone (Fig. 2a) had an intensity T2.5 and after three hours, the location of its center was at 16.7°N/61.9°E with unchanged intensity. However, its rapid intensification continued and it further increased

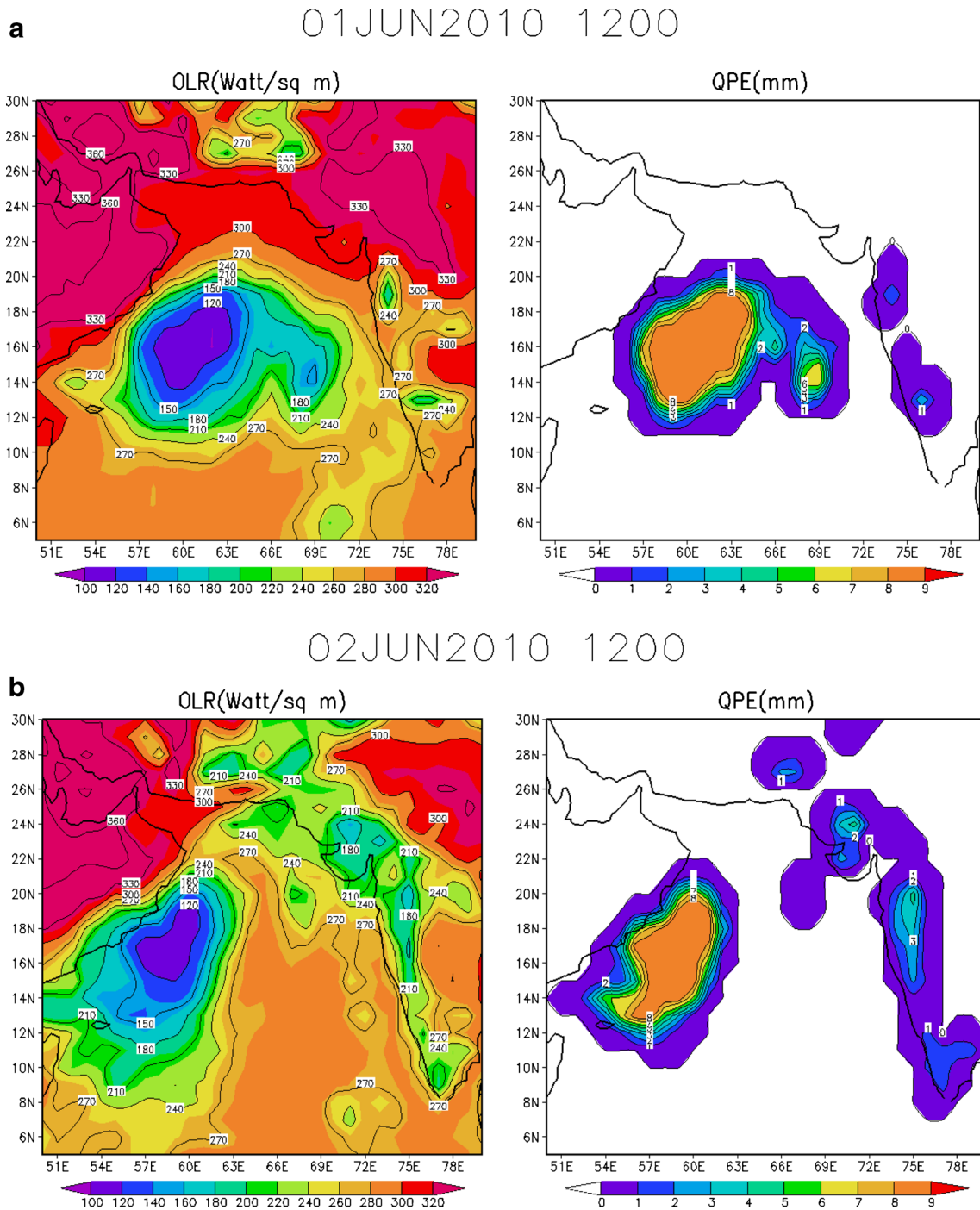


Fig. 2 Variation of OLR (Wm^{-2}) and QPE (mm) over Arabian Sea from KALPANA-1 geostationary satellite at 1200 UTC on (a) June 01 and (b) June 02, 2010. The left panel is for OLR and the right panel is for QPE.

The x-axis is for longitude variation (in degrees) and the y-axis is for latitude variation (in degrees)

to T3.0 at 1800 UTC (on June 01) with center located at 17.0°N/61.8°E. The intensity of the vortex increased to T3.5 at 2300 UTC (on June 01), when its eye was visible and the center was at 17.5°N/61.0°E (figure not shown for brevity). The eye of the cyclonic system continued to be visible thereafter and the center of the system was located at 17.5°N/60.9°E with intensity T3.5 at 0000 UTC on June 02, 2010. The intensity of the cyclone further jumped to T4.0 at 0500 UTC on June 02 and was located with a center at 17.9°N/60.3°E having an intensity of T4.5 after four hours. At this hour (i. e. at 0900 UTC on June 02), the vortex of the cyclonic system was found to be moving slowly in north-west direction. Such a movement can also be noticed even at 1200 UTC on the same day (Fig. 2b). The system attained maximum intensity of very severe cyclonic storm with maximum sustained wind speed of 43.73 ms^{-1} on June 02.

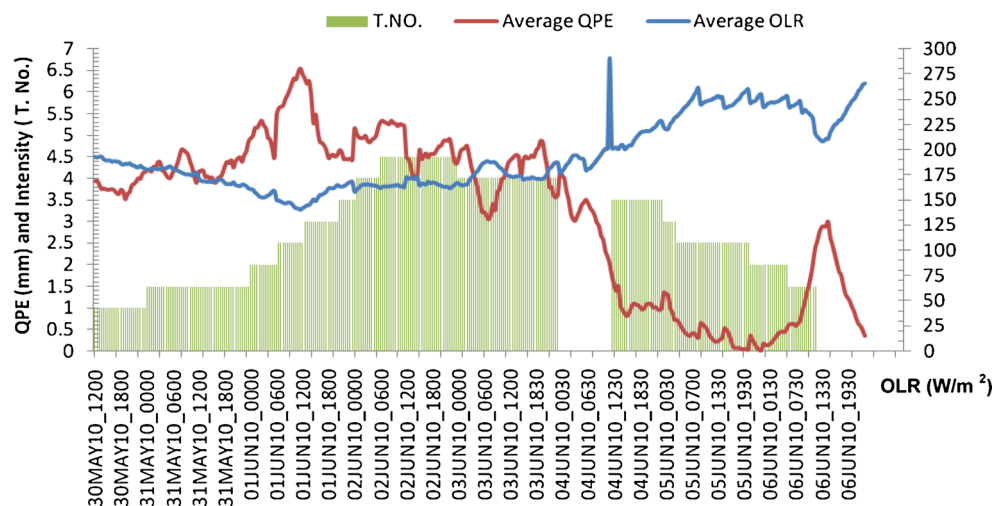
The cyclonic system showed a sign of being weakened at 0000 UTC on June 03, 2010, when the intensity decreased to T4.0 with center at 18.4°N/59.7°E (figure not shown for brevity). It maintained its north-west movement and intensity till it crossed the coast at 0300 UTC (on June 03), when its center was at 21.8°N/59.4°E. The system crossed Oman coast as a severe cyclonic storm with the wind speed of about 33.44 ms^{-1} near latitude 21.50°N. After crossing over the coast, it assumed north/north-easterly movement. At 1200 UTC on June 04, 2010, it again entered into Arabian Sea (Fig. 1) when its center was located near 22.8°N/59.3°E. At this hour the intensity of the cyclonic system was T3.5. The cyclonic system had entered into the land on the 3rd day of depression and it came back again to the Arabian Sea almost after 15 h. It moved parallel but close to Makaran coast and crossed Pakistan coast as a depression, close to south of Karachi on June 06. It then moved east-north-eastwards across south Pakistan and Rajasthan and weakened gradually into a well-marked low pressure area over adjoining northwest Madhya Pradesh on June 07, 2010.

During the life cycle of the tropical cyclone PHET, the KALPANA-1 satellite derived intensity and the near surface wind speed go hand in hand with the trends being similar to each other (figure not shown). The maximum wind speed was observed at 0600 UTC on June 02, 2010 that remained constant up to 1800 UTC on the same day and decreased afterwards.

The variation of average OLR, average QPE and intensity of tropical cyclone PHET is depicted in Fig. 3. The OLR values are computed using half hourly data from KALPANA-1 with the help of a special satellite algorithm designed for such calculations and the desired data was obtained from National Satellite Data Centre, IMD. The average values of QPE and OLR were computed over the region of $7^\circ \times 7^\circ$, where the center of this area is the center of the cyclonic system. The comparative analysis of the variation of QPE, OLR and TC intensity of PHET indicates an inverse relationship between OLR and QPE i. e. the value of OLR is more at a time when QPE is less and vice versa. The TC intensity shows as usually an increasing behaviour with the intensification of the cyclonic system and then a decreasing behaviour as the cyclonic storm undergoes the decaying stage.

The variation in QPE (average value over the chosen area) was observed in between 0 and 7 mm and the corresponding range of OLR was $150\text{--}275 \text{ Wm}^{-2}$ in every 3 h (Fig. 3). Maximum of the averaged QPE was observed on June 01, 2010 during the period 0600 to 1200 UTC. On the other hand, average OLR was observed to be of minimum value in the same span of time on the same day (Fig. 3). A decreasing (increasing) trend in the average QPE (OLR) was observed after 1200 UTC on June 01, 2010. In this case study, the cyclone intensity was T2.5 when average QPE was observed to be of maximum value while the value of average OLR was at minimum. The maximum intensity (T4.5) was observed at 0600 UTC on June 02, just after 24 h of attaining the maximum and minimum values of QPE and OLR respectively.

Fig. 3 Variation of average OLR (out going long wave radiation), average QPE and intensity with date and time (in UTC) during the occurrence of PHET. The x-axis represents date and time (in UTC) and y-axis represents QPE (in mm), OLR (in Wm^{-2}) and intensity (in terms of T. No.)



From this analysis, it may be inferred that the cyclone can reach its maximum intensity after about a day of maximum QPE and minimum OLR.

Genesis of PHET

To undergo tropical cyclogenesis, there are several favourable precursor environmental conditions that must be in place (e. g. Gray 1979) over north Indian Ocean. In order to understand and depict such conditions, several satellite derived parameters are analysed in this study. For instance, the sea surface temperature (SST) derived from MODIS, TMI microwave radiometer (launched aboard Tropical Rainfall Measuring Mission (TRMM) satellite) and AMSR-E instrument (carried on board the Aqua satellite) is shown in Fig. 4 as a composite. For the necessity of the development of a TC, ocean water should be warm enough (at least 26.5 °C), throughout a sufficient depth (at least in the order of 50 m) to fuel the heat engine of the tropical cyclone. Usually, the atmosphere cools fast enough with height such that it is potentially unstable to moist convection. It is the thunderstorm activity, which allows the heat stored in the ocean waters to be liberated for the tropical cyclone development.

Figure 5a depicts CIMSS (Cooperative Institute for Meteorological Satellite Studies; University of Wisconsin, Madison, United States) - McIDAS (Man computer Interactive Data Access System) generated 850 hPa relative vorticity (RV) from METEOSAT-7 at 0900 UTC on June 03, 2010. At this hour, the RV is very high near Oman coast in the genesis region, as compared to the surroundings. TCs cannot be generated spontaneously since they require a weakly organized system with sizable spin and low level inflow. The existence of high RV (100–250; unit: circulation per unit area)

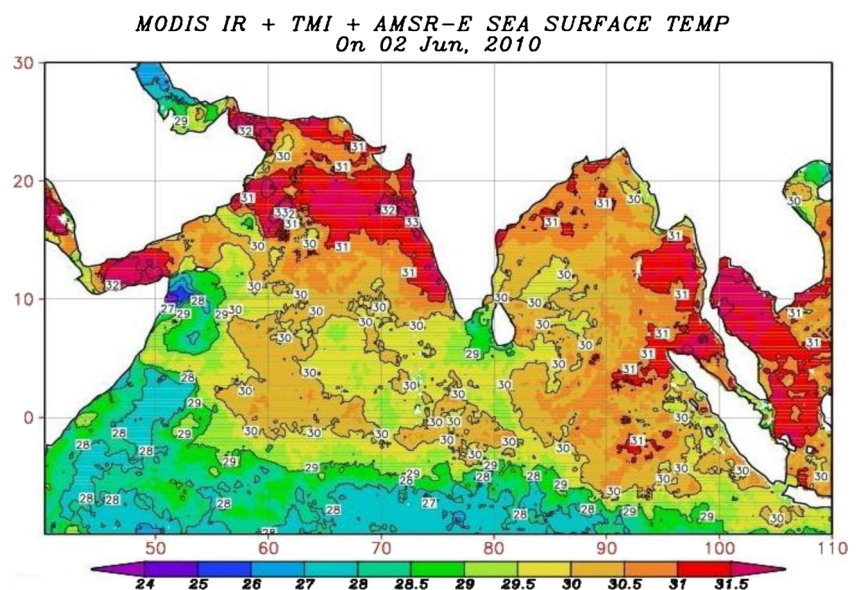
was a favourable condition for the development and propagation of PHET. Similarly, the METEOSAT-7 wind shear product at 0900 UTC on June 03, 2010 (Fig. 5b) indicates that the wind shear is very low (less than about 10 ms⁻¹ or 20 knots) in the genesis region. Large values of vertical wind shear disrupt the incipient cyclone and can prevent genesis. If a cyclone has already formed, large vertical shear can weaken or destroy it by interfering with the organization of deep convection around its center. A minimum amount of low level wind shear (up to 10 knots or 5.144 ms⁻¹) is required to build the environment for the occurrence of the cyclone and wind shear up to 20 knots (~10.28 ms⁻¹) will help to maintain it.

In addition, the relative humidity in mid and upper layers of the atmosphere should be large enough for the survival and intensification of a cyclonic system. KALPANA-1 measurements show large values of upper tropospheric humidity at the genesis region of PHET (figures not shown). The dry mid-levels are not conducive for allowing the development of widespread thunderstorm activity during a cyclone. The energy input to the system is from warm water and humid air over tropical oceans and the release of heat is through condensation of water vapour to water droplets or rain. Only a small percentage (~3 %) of this released energy is converted into kinetic energy to maintain the circulation in it.

Numerical Model and Experimental Design

The cyclonic system PHET is simulated using WRF modeling system. The WRF modeling system is one of the advanced mesoscale models used widely for both research and operational purposes. It has several modules and the mesoscale version has primarily two cores: (i) Advanced Research WRF (ARW) and (ii) Non-hydrostatic Mesoscale Model

Fig. 4 Satellite derived sea surface temperature (in °C) over north Indian ocean for June 02, 2010 (1200UTC). The x-axis indicates the longitudes (in degree) and y-axis indicates the latitudes (in degree)



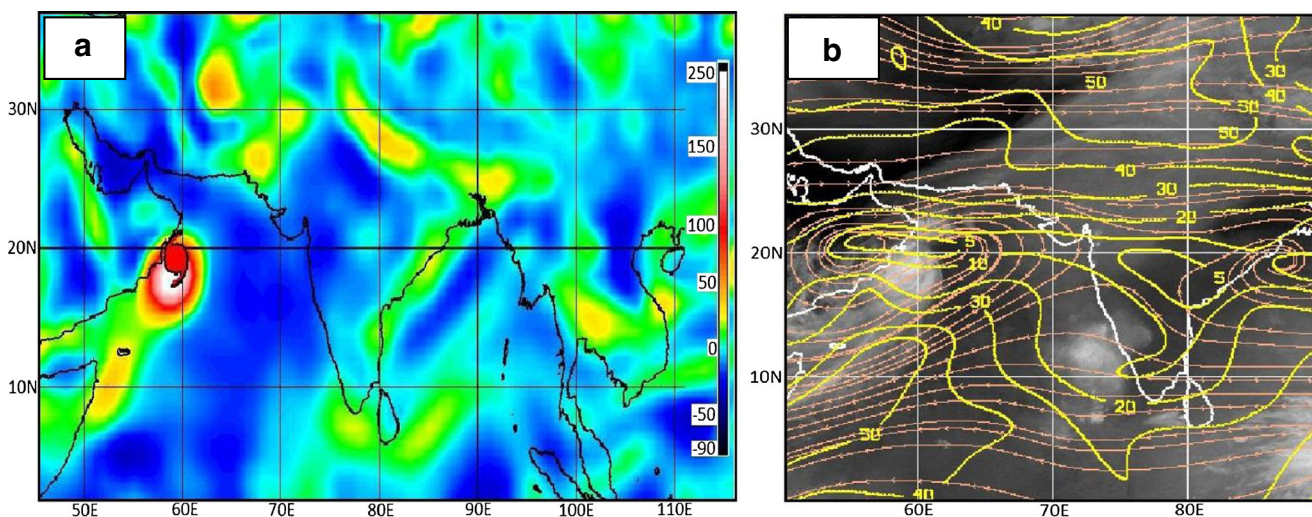


Fig. 5 (a) METEOSAT-7 derived 850 hPa relative vorticity $\times 10^5$ (unit: circulation per unit area) at 0900 UTC June 03, 2010. (b) wind shear (in Knots; $1 \text{ knot} \sim 0.5144 \text{ ms}^{-1}$) between surface and upper troposphere from METEOSAT-7 in north Indian ocean at 0900 UTC on June 03, 2010. The relative vorticity product and wind shear was generated by CIMSS

(Cooperative Institute for Meteorological Satellite Studies; University of Wisconsin, Madison, USA) - McIDAS (Man computer Interactive Data Access System) software (Courtesy of CIMSS, University of Wisconsin, USA). Here, the x-axis indicates the longitudes (in degree) and y-axis indicates the latitudes (in degree)

(NMM). The present study uses ARW core of the WRF modeling system version 3.1 (Skamarock et al. 2008). The model is configured using a single domain with 27 km horizontal resolution with 131 grid points in both east–west and north–south direction. The vertical resolution of the model contains 38 eta levels with 50 hPa as the model top. The central latitude and longitude of the domain was considered to be 17.5°N and 61.5°E respectively. The CONTROL simulation is carried out using the initial and boundary conditions from six hourly global FNL data (from Global Forecasting System) of $1^\circ \times 1^\circ$ resolution (<http://dss.ucar.edu/datasets/ds083.2/data/>).

The model experiments consider a set of physics and dynamics for simulating the characteristic features of PHET. The CONTROL simulation considers Dudhia (1989) short-wave radiation parameterization, Rapid Radiative Transfer Model (RRTM) for long wave radiation (Mlawer et al. 1997), WRF single-moment 3-class microphysics scheme (Hong et al. 2004), Grell-Devenyi (G-D) ensemble cumulus convection scheme (Grell and Devenyi 2002), Unified Noah land-surface model (Chen and Dudhia 2001) and Yonsei University (YSU) boundary layer scheme (Hong et al. 2006). The surface layer scheme used along with the boundary layer parameterization is based upon Monin-Obukhov (M-O) approach. These parameterization schemes are chosen in order to maintain the consistency with the operational setting used for numerical weather forecasting purpose at IMD. Since convection is a significant aspect of the development and propagation of a TC, the cumulus physics may play a major role in determining its characteristic features. Thus, the sensitivity experiments are carried out with respect to various cumulus parameterizations available in WRF-ARW modeling

system (version 3.1). The sensitivity experiment “SENKF” considers Kain-Fritsch (K-F) scheme (Kain and Fritsch 1990 and 1993; Kain 2004), the “SENBMJ” simulation considers Betts-Miller-Janjic (BMJ) scheme (Betts and Miller 1986; Janjic 2000) and the “SENGR3D” simulation considers Grell -3D cumulus parameterization in place of G-D ensemble scheme. All of the simulations carried out in the present study take into account cloud cover effect. However, snow cover effect is not included. All the simulations are done in non-hydrostatic mode and use second order diffusion in coordinate surface along with third order Runge–Kutta time integration technique.

Each of the model simulations is carried out for 78 h starting from 1800 UTC on June 01, 2010. The initial time was primarily decided on the basis of the observations relating to development and propagation of the tropical cyclone, availability of satellite measurements and model spin-up period. In addition, it was perceived that 2–3 days simulation would be usually sufficient to show the model capability in a short term forecasting scenario.

Simulated Results

The numerical prediction of track, intensity, time of landfall, wind and rainfall over the regions affected by the cyclone are some of the important parameters while dealing with the forecasting of a TC. An accurate track prediction is most critical to determine; which is the geographical location where maximum damages due to wind and rain are expected to occur. A misplaced cyclone center by the model forecast would produce inaccurate location of landfall and strength of

the cyclonic circulation at the actual point of landfall. Thus, the track prediction is crucial to locate areas of heavy rainfall and wind. The computational experiments conducted in this study are mainly for investigating the influence of cumulus parameterizations. However, some of the WRF model simulated features from the CONTROL experiments are also discussed in this section in order to understand whether the observed meteorological features are qualitatively reproduced by the model or not. It may be noted that the CONTROL experiment considers the same set of physics and dynamics as that of the operational set-up of IMD. However, it does not represent the operational results.

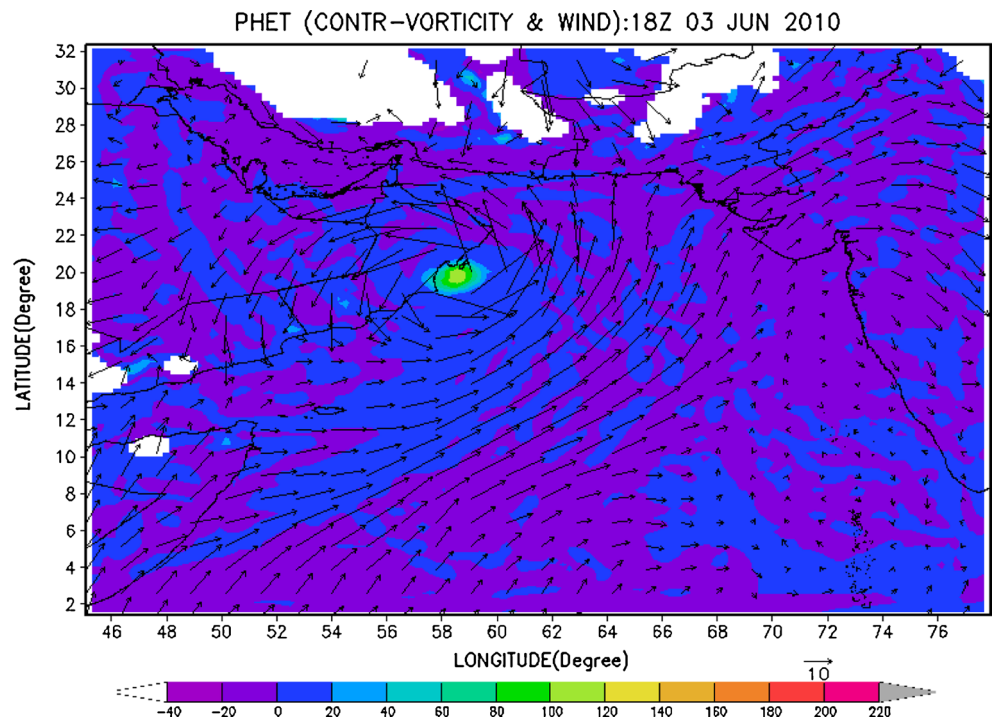
The METEOSAT-7 derived relative vorticity at 0900 UTC on June 03, 2010 shows the relative vorticity before the landfall of the tropical cyclone PHET (Fig. 5a) at Oman coast. On the other hand, the CONTROL experiment indicates a delay (at least 7–8 h) in the landfall of the cyclone at Oman coast since the model computed relative vorticity at 1800 UTC on June 03 shows the center of the cyclonic storm is about to cross the Oman coast (Fig. 6). However, the simulated center of the tropical storm indicates higher relative vorticity (140×10^{-5} circulation per unit area) as compared to the surroundings within the domain, which qualitatively agrees with that of the satellite estimation. It may be noted that the wind field demonstrating the cyclonic circulation are qualitatively well represented around the center of the tropical storm, where the maximum relative vorticity is obtained (Fig. 6). While the maximum simulated relative vorticity at the center of the cyclone ranges from 100 to 140 ($\times 10^{-5}$) in magnitude (figure not shown), the corresponding value estimated from

METEOSAT-7 observations is within a range 100–250 ($\times 10^{-5}$) as evident from Fig. 5a.

Unlike the KALPANA-1 derived OLR pattern, where the minimum values of OLR ($100\text{--}120 \text{ Wm}^{-2}$) is observed to be at the cyclogenesis region (e. g. Fig. 2), the model simulates the minimum values ($75\text{--}100 \text{ Wm}^{-2}$) at the peripheral area around its central core in the CONTROL experiment (e. g. Fig. 7a). Similarly, the computed maximum rainfall ($600\text{--}650 \text{ mm/3 h}$) from the CONTROL simulation is found to be at the peripheral area unlike that of the KALPANA-1 derived QPE pattern, which is observed to be maximum ($8\text{--}9 \text{ mm}$; computed using Arkin’s technique given in Arkin et al. 1989) at the central core of the tropical storm. Even though the maximum observed QPE qualitatively correspond to the minimum OLR derived from KALPANA-1, the simulated maximum rainfall do not seem to be at the same area as that of the OLR minimum (Fig. 7–8). However, the model simulated minimum OLR ($75\text{--}100 \text{ Wm}^{-2}$) quantitatively closer to those derived from KALPANA-1 observations ($100\text{--}120 \text{ Wm}^{-2}$).

In order to understand the moisture transport and its relation to the occurrence of rainfall during PHET tropical storm, vertically integrated water vapour mixing ratio is computed between 1000 and 200 hPa pressure levels using a similar method as followed by Howarth (1983) and Felton et al. (2013). The vertically integrated moisture transport (Fig. 8) is computed using the horizontal wind components (ms^{-1}) in addition to the water vapour mixing ratio (kg.kg^{-1}). The computation is made over 72 h starting from 00 UTC June 02, 2010 and the accumulated rainfall is depicted also in Fig. 8

Fig. 6 850 hPa wind (unit: ms^{-1}) and relative vorticity (unit: circulation per unit area) from CONTROL simulation at 18 UTC on June 03, 2010. The values of relative vorticity are multiplied by 10^5



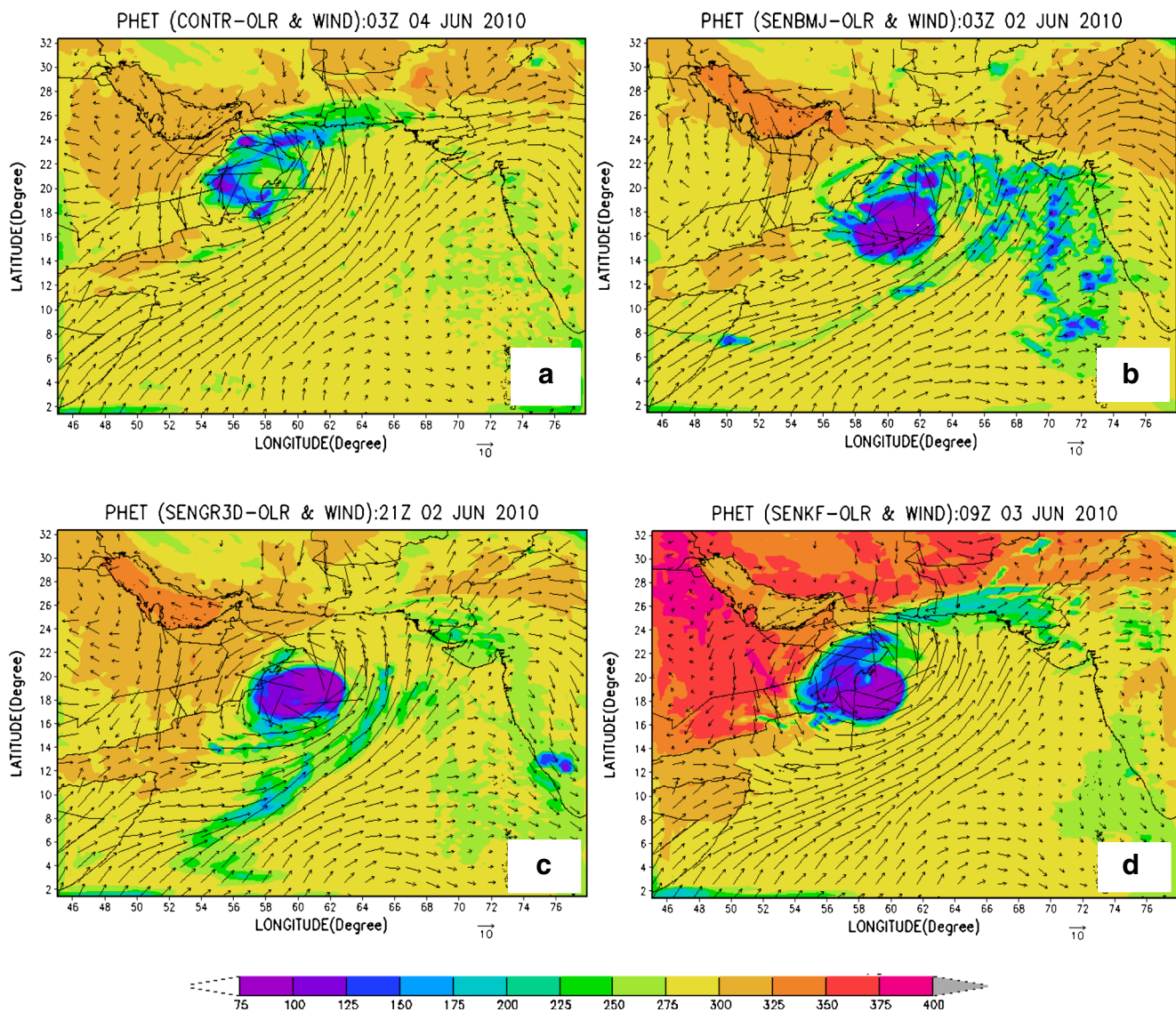


Fig. 7 850 hPa wind (unit: ms^{-1}) and outgoing long-wave radiation (unit: Wm^{-2}) from various simulations: (a) CONTROL experiment at 03 UTC on June 04, (b) SENBMJ experiment at 03 UTC on June 02, (c)

SENG3D experiment at 21 UTC on June 02 and (d) SENKF experiment at 09 UTC on 03 June, 2010. The arrows indicate the wind field whereas the shaded contours are for OLR

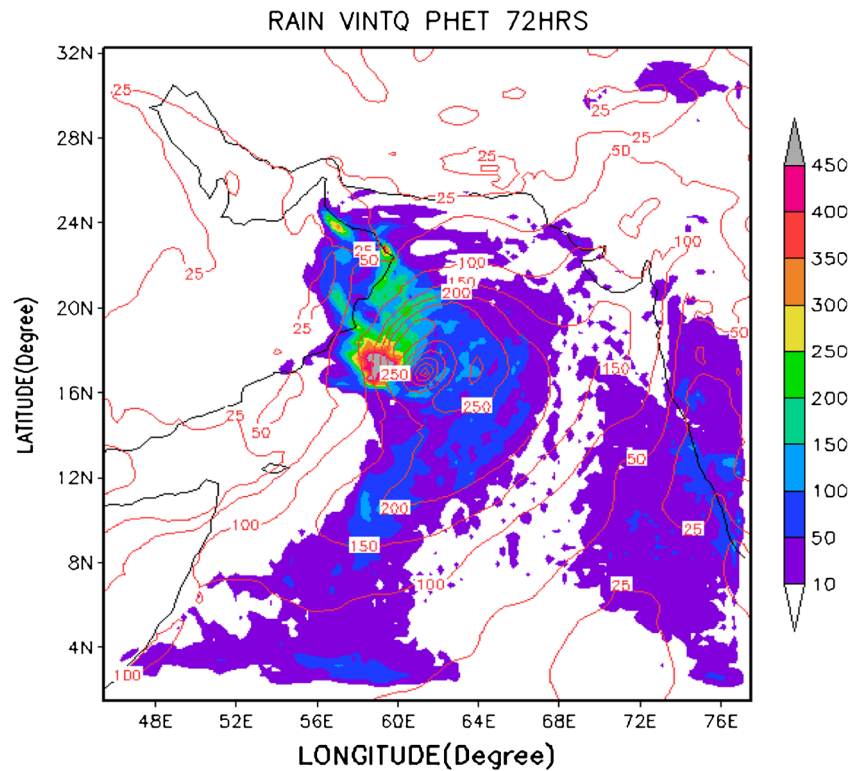
accordingly, besides the vertically integrated moisture transport. The Fig. 8 indicates that the availability of moisture is found to be maximum in and around the genesis region. Increased wind variability usually creates a positive feedback cycle between surface winds and convection with enhanced evaporation supporting enhanced atmospheric convection (Felton et al. 2013). Consequently, the thunderstorm activity in and around the genesis region, due to enhanced convection supports the occurrence of heavy precipitation. In this case, the maximum rainfall in Oman coast is because of the very typical thunderstorm activity and availability of maximum moisture in and around the genesis region. The transport of moisture towards the genesis region is due to the generic nature of the flow pattern in the tropical cyclone as evident in Fig. 6 and 7.

Impact of cumulus convection parameterizations

The cumulus convection physics parameterization in principle should play a major role in governing the characteristic features during the occurrence of a tropical storm like that of PHET. In view of this, the relative performance of K-F, Grell-3D, BMJ and G-D schemes is discussed in this section in order to understand the performance of these schemes during the occurrence of the tropical storm in the west coast of India over Arabian Sea.

The qualitative analysis of relative vorticity from sensitivity experiments with respect to cumulus convection schemes suggests that the inference in relation to maximum vorticity at the center of the tropical cyclone (as described in section 2 and 3) also holds good. However, in the quantitative prospective,

Fig. 8 Vertically integrated (between 1000 hPa and 200 hPa) water vapour mixing ratio (kg.kg^{-1}) and accumulated rainfall (mm) during 00 UTC June 02 to 00 UTC June 05, 2010 (72 h). The contours signify the vertically integrated moisture transport and the shaded plots are for 72 h accumulated rainfall



the maximum relative vorticity at the center of the tropical cyclone increases approximately by 28 % in SENBMJ experiment and the corresponding increase is 70 % or more in case of SENGR3D and SENKF experiments. It may be noted that the time at which the maximum value of simulated relative vorticity at the center of the tropical storm for various experiments is not necessarily same (figure not shown for brevity).

While the minimum OLR values at the central core is maintained for a longer time during the propagation of the tropical cyclone in observational prospective (discussed in section 2), such a feature is less visible in CONTROL experiment (e. g. Fig. 7a). In contrast, the sensitivity experiments show this meteorological feature for few hours (Fig. 7b-d). The SENBMJ and SENGR3D experiments only show this meteorological feature properly at 03 UTC (Fig. 7b) and 21 UTC (Fig. 7c) on June 02, 2010 respectively. However, this feature is more prominent in SENKF experiment for few hours from 15 UTC June 02 (figure not shown) to 09 UTC June 03, 2010 (Fig. 7d). The minimum value of OLR from the SENBMJ and SENKF experiment is found to be less than 75 Wm^{-2} . On the other hand, the corresponding minimum value is greater than 75 Wm^{-2} in CONTROL and SENGR3D experiments. It may be noted that the simulated minimum is not necessarily computed at the same time.

The center of the maximum accumulated rainfall (three hourly) in sensitivity experiments, does not go hand in hand with the central core of the tropical cyclone (figures not shown for brevity) similar to that of CONTROL simulation but

contrasting to the observed QPE pattern from KALPANA-1 (Fig. 2). The amount of maximum three hourly accumulated rainfall predicted by SENBMJ, SENGR3D and SENKF experiments is found to be always greater than that of the CONTROL experiment. For example, the maximum difference of three hourly accumulated precipitation from SENBMJ experiment with respect to CONTROL simulation, is found to be more than 500 mm at 12 UTC on June 04, 2010 (around the central core of the cyclonic storm).

The cumulus parameterization schemes considered in this study are usually responsible for the sub-grid-scale effects of convective and/or shallow clouds in WRF model simulations. The schemes are intended to represent vertical fluxes due to unresolved updrafts and downdrafts and compensating motion outside the clouds. The K-F scheme (Kain 2004; Kain and Fritsch 1990 and 1993) utilizes a simple cloud model with moist updrafts and downdrafts, including the effects of detrainment, entrainment, and relatively simple microphysics. The BMJ scheme (Janjic 1994 and 2000) is primarily derived from Betts-Miller convective adjustment scheme (Betts and Miller 1986). The BMJ scheme considers cloud efficiency, which in turn depends upon entropy change, precipitation and mean temperature of cloud. The G-D ensemble scheme (Grell and Devenyi 2002) is based on multiple mass-flux type schemes, which are effectively dependent on convective available potential energy (CAPE), low level vertical velocity or moisture convergence. However, these cumulus schemes

within G-D ensemble scheme differ in updraft and downdraft entrainment and detrainment parameters, and precipitation efficiencies. Grell-3D scheme bears similarities with G-D ensemble scheme. However, the Grell-3D scheme does not include quasi-equilibrium approach among ensemble members and allows subsidence effects to be spread to neighbouring grid columns unlike other schemes. All these cumulus schemes differ in triggering mechanisms as well. While BMJ scheme does not consider cloud detrainment other schemes do. However, all of the other schemes are mass-flux based schemes unlike BMJ (mass adjustment). The BMJ scheme considers sounding adjustment, whereas K-F scheme considers CAPE removal closure technique. On the other hand, both G-D and Grell-3D ensemble schemes consider various closure techniques. In view of these broad differences, the performances of the various cumulous schemes considered in this study, differ from each other while the model computes OLR and precipitation. The performance of cumulus schemes is merely based on specific case and may not be consistent for all tropical cyclones occurring even in a particular basin like Arabian Sea or Bay of Bengal.

Comparison of Observed and Simulated Track

The comparison of IMD observed and predicted track with those from CONTROL and sensitivity experiments with cumulus convection physics available in WRF (version 3.1) modeling system indicates that the simulated track from SENBMJ experiment does not cross the Oman coast unlike that of the other tracks (Fig. 9). Further, the simulated tracks from CONTROL and SENG3D experiments are almost similar to each other after the cyclone crosses Oman coast. However, the cyclone track from SENKF experiment seems to follow the IMD observed or predicted track after 21 UTC June

04, 2010 even though the track looks similar to that of the CONTROL simulation before this time. The minimum and maximum errors of the simulated track from CONTROL experiment are 42 km (at 06 UTC on June 03) and 392 km (at 00 UTC on June 05) respectively. The corresponding values for SENBMJ experiment are 40 km (at 06 UTC on June 02) and 286 km (at 00 UTC June 05), for SENG3D experiment are 44 km (at 00 UTC June 02) and 433 km (at 00 UTC June 05) and for SENKF experiment are 25 km (at 18 UTC June 02) and 396 km (at 00 UTC June 05) respectively. Thus, the track error increases significantly after 78 h of simulation irrespective of the cumulus parameterizations. However, the cyclone track qualitatively shows to be better predicted in SENBMJ experiment as when compared to IMD predicted track.

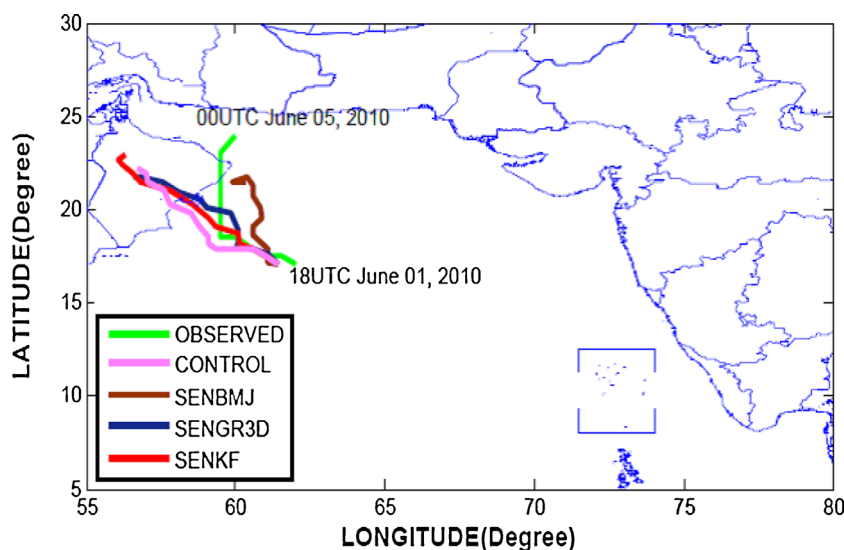
Concluding Remarks

This study emphasizes upon the observed and simulated meteorological features during the occurrence of the tropical cyclone PHET over Arabian Sea. The observed meteorological features of this cyclone presented in this study, are primarily from various satellite products including those from KALPANA-1, METEOSAT-7 and MODIS.

The tropical cyclone occurred for several days and the objective of the study primarily was to see the performance of the model and more specifically, that of cumulus physics parameterizations. In view of this, most intensive period of the cyclone was chosen for simulation purpose using WRF modeling system (version 3.1). The model was initiated at 18 UTC on June 01, 2010.

The METEOSAT-7 observed significantly high values (i. e. 100–250; unit: 10^{-5} s^{-1}) of relative vorticity in the genesis region of PHET. However, the model simulates a significantly

Fig. 9 Comparison of IMD observed/predicted track of PHET with those from CONTROL, SENBMJ, SENG3D and SENKF experiments during 18 UTC June 01–00 UTC June 05, 2010



low value of relative vorticity (i. e. maximum value of 140; unit: 10^{-5} s^{-1}) in the genesis region. The BMJ scheme predicts lower values of maximum vorticity in the genesis region as compared to that of G-D scheme. However, the use of Grell-3D scheme further improves the prediction and the performance of K-F is better as the maximum predicted value of relative vorticity in the genesis region (>220) is closer to the observed one (250).

The CIMSS-McIDAS generated wind shear is found to be very low (less than about 10 ms^{-1} or 20 knots) in the genesis region of PHET. Therefore, the prevailing wind shear is found to be quite suitable for the propagation of the cyclone. The upper tropospheric humidity (UTH) was found to be very high during the occurrence of PHET with values 90–100 % or even more in the genesis region, which is quite supportive for the propagation and intensification of the cyclonic storm.

A qualitative analysis of OLR and QPE from KALPANA-1 satellite suggests that the maximum values of QPE were observed when there was minimum OLR. A similar result was also obtained from various simulations including the CONTROL experiment and sensitivity experiments with respect to the cumulus schemes. However, the K-F scheme shows a better pattern of the OLR distribution in the genesis region as when compared to that of observations from KALPANA-1 satellite.

A comparative analysis of the variation of QPE, OLR and TC intensity of PHET indicates an inverse relationship between OLR and QPE i. e. the value of OLR is more at a time when QPE is less and vice versa. It was observed that the cyclone could reach its maximum intensity after about a day of maximum QPE and minimum OLR. The intensity of the tropical cyclone shows as usually an increasing behaviour since the system is intensified and thereafter a decreasing behaviour is observed as the cyclonic storm undergoes the decaying stage. During the life cycle of the tropical cyclone PHET, the surface wind speed and the intensity go hand in hand and they are positively correlated.

The qualitative analysis indicates that K-F scheme performs reasonably well for simulating various parameters during the occurrence of the tropical cyclone PHET though none of the schemes is very much sensitive to the track prediction. The reason behind a relatively better performance of K-F scheme is probably due to the possible consideration of CAPE removal closure technique. Since CAPE is a significant parameter in determining the moist stability and plays a vital role in case of the atmosphere containing clouds. And, K-F scheme allows non-precipitating clouds for any updraft that does not reach minimum cloud depth for precipitating clouds. Therefore, the computation of OLR and precipitation in the model significantly get influenced. However, this performance does not guarantee that the scheme would be able to give a better result in other tropical cyclone cases. Thus, the performance of a cumulus parameterization is highly dependent upon tropical

cyclone cases and must be tested before drawing any general conclusion. A recent study by Osuri et al. (2012) showed that K-F scheme in combination with YSU boundary layer parameterization performs better in tropical cyclone prediction over north Indian Ocean region. Our findings also largely agree with the studies by Osuri et al. (2012) though it is recommended that the performance may still vary from case to case basis as the results indicate in the case study of PHET.

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