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Impact of satellite derived winds and cumulus physics during the occurrence of the tropical cyclone Phyan

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Abstract

The quantitative data such as satellite derived winds are useful for improvement of the numerical prediction of weather events like tropical cyclones. In this study, the satellite derived winds from QuikSCAT surface observations and KALPANA-1 atmospheric motion vectors are used during the cyclone PHYAN in order to update the initial and boundary conditions through three-dimensional variational assimilation technique within the Weather Research Forecasting (WRF) modeling system. The simulated mean sea level pressure and 850 hPa wind fields from eight experiments are presented in this study in order to analyze the observed and simulated features of the tropical cyclone PHYAN that occurred in the month of November, 2009. The model results are also compared with the KALPANA-1 images and the India Meteorological Department (IMD) predicted results. Further, the intensity and track of the cyclonic storm PHYAN, generated from the simulations are also compared with the IMD predictions in order to evaluate the model performance.

Keywords: WRF modeling system, variational assimilation, satellite derived winds, cloud motion vectors, cyclonic storm

Introduction

A tropical cyclone is a rotational low pressure system in tropics when the central pressure falls by 5 to 6 hPa from the surrounding and maximum sustained wind speed reaches about 62 kilometers per hour. The tropical cyclonic storms are usually recognized as one of the important issues within the scientific community since they happen to be responsible for damages at coastal areas in tropics. However, it is accepted that the damage has been increased all over the world due to the cyclonic storms even though the studies show that there is decadal variations and there is no definite long-term trend in the frequency or intensity of tropical cyclones (Raghavan & Rajesh, 2003). On the other hand, the studies regarding the tropical cyclones have been intensified over the years and a number of efforts are still made in order to enhance the understanding in this direction. Besides modeling efforts, the satellite images and products are also very useful for this purpose. However, the satellite data might also be used for the improvement of the model prediction as well through satellite data assimilation.

The thrust for satellite data assimilation has been evolved during the last decade and is expected to continue in future as well. In recent years, the satellite data has become a useful source in the study of tropical cyclones and very less study is available in literature that use the satellite derived winds for predicting the cyclone track and intensity. Singh *et al.* (2008) have used Special Sensor Microwave Imager (SSM/I) and Quick Scatterometer (QuikSCAT) satellite observations in order to study the impact on the simulation of the Orissa super cyclone (that occurred over the Bay of Bengal in October 1999) using three-dimensional variational assimilation (3DVAR) technique in the fifth-generation Pennsylvania State University-National Center for Atmospheric Research Mesoscale Model (MM5). Zhihua *et al.* (2005) assimilated QuikSCAT data using 3DVAR technique within MM5 model in order to examine the effect on the numerical simulation of typhoon track and intensity. They found that the tracks of 11 typhoons out of 12 and intensity of 10 typhoons out of 12 cases were improved in 24 hour prediction. Most of the earlier studies based on cyclonic storms using QuikSCAT data for assimilation purpose utilized MM5 model and these studies are very rare. However, the present study uses 3DVAR technique within Weather Research Forecasting (WRF) modeling system in order to examine the impact of the satellite derived winds from QuikSCAT and KALPANA-1 on the prediction of track and intensity of the cyclonic storm PHYAN. Over the ocean the observations are rare especially during the cyclonic systems and these data sparse regions are major source of forecast error in numerical models.

This is especially true in cyclone track prediction, where lack of conventional tropospheric observations over oceanic regions can lead to erroneous depictions of the environmental flow that accounts for much of the storm motion. Operational meteorological satellites have the ability to sample the large-scale oceanic environment frequently, making them prime tools for monitoring the tropical cyclones like PHYAN. While imagery is an essential and routinely utilized component for qualitative applications, reliable and high density quantitative observations are necessary to improve the numerical weather prediction of a tropical cyclone. Such improvements can reduce the errors in cyclone track forecasts. An effort is made in this study in order to utilize

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Table 1. Model configuration and physics considered during the simulations

Horizontal grid distance	27 km
Integration time step	90s
Number of grid points	121 in both west-east as well as south north directions
Number of met grid levels	27
Number of vertical model eta levels	38
Model eta levels	1.000, 0.994, 0.983, 0.968, 0.950, 0.930, 0.908, 0.882, 0.853, 0.821, 0.788, 0.752, 0.715, 0.677, 0.637, 0.597, 0.557, 0.517, 0.477, 0.438, 0.401, 0.365, 0.332, 0.302, 0.274, 0.248, 0.224, 0.201, 0.179, 0.158, 0.138, 0.118, 0.098, 0.078, 0.058, 0.038, 0.018, 0.000,
Model top	50 hPa
Microphysics	WSM 3-class simple ice scheme
Radiation scheme (long wave)	RRTM scheme
Radiation scheme (short wave)	Dudhia's short wave radiation
Surface layer physics	Monin-Obukhov scheme
Land-surface physics	Unified Noah land-surface model
Boundary layer physics	Yonsei University (YSU) scheme
Cumulus convection	Grell-Devenyi (GD) ensemble scheme Kain-Fritsch (KF) scheme Betts-Miller-Janjic (BMJ) scheme Grell -3D cumulus parameterization
Dynamic option	Eulerian mass
Time integration	3rd order Runge-Kutta
Diffusion	2nd order diffusion in coordinate surface
Mode of simulation	Non-hydrostatic
Map projection	Mercator
Number of domain	Single
Central point of the domain	Central latitude: 16.40N ; Central longitude: 74.00E
Initial and boundary conditions	3-dimensional real data (FNL:1^{O}X1^{O})

and incorporate the satellite observations with model analyses through the observational processor of the variational assimilation system so that the results from WRF modeling system could be improved**.** The present study uses QuikSCAT surface winds and cloud motion vectors (CMV) and water vapor winds from KALPANA-1 geostationary satellite in order to study the recent cyclonic storm PHYAN that occurred in November 2009 over the Arabian Sea. The satellite derived winds from QuikSCAT and KALPANA-1 are used to update the initial and boundary conditions from WRF modeling system through 3DVAR technique. The quality of data used is similar to European satellite, Meteosat -7 derived AMVs (Deb *et al,* 2008) and with quality index ≥ 0.8 is used.

The details of the numerical model, experimental design and data processing are discussed in the following section. The results from the present study are described in section 3 and section 4 briefly summarizes the significant conclusions.

Numerical model, experimental design and data used

The present study uses advanced research WRF (ARW) modeling system version 3.1 (Skamarock *et al.,* 2008) that became a reality due to multi institutional effort. It is based upon a set of governing equations (Ooyama, 1990) that are solved using the initial and periodic boundary conditions as provided to the model. In this study, the experiments (Table 2) such as CONTROL, SENKF, SENBMJ and SENGR3D simulations are carried out using the initial and boundary conditions from six hourly NCEP (National Center for Environmental Prediction) / NCAR (National Center for Atmospheric Research) global final analysis data of 1^{o}x1^{o} resolution (http://dss.ucar.edu/ datasets/ds083.2/data/). However, in other experiments (Table 2) the model initial and boundary conditions are updated using the satellite surface wind measurements from QuikScat and atmospheric motion vectors from KALPANA-1 satellites through 3DVAR technique within WRF modeling system. The QSCAT experiment or simulation considers QuikSCAT surface wind measurements, the K1CMV simulation takes into account the cloud motion vectors of KALPANA-1 satellite, the K1WVW simulation considers water vapor winds from KALPANA-1 and the QSCATK1 experiment considers both the QuikSCAT surface winds as well as the KALPANA-1 atmospheric motion vectors (i.e. a combination of CMV and water vapor winds). It may be noted that the sea surface winds scatterometer onboard the QuikSCAT satellite is microwave radar launched and operated by United States National Aeronautics and Space Administration (NASA). It provided spatially extensive measurements of near surface wind speeds and directions over the world's oceans from July 1999 to November 2009. It sampled more than 90% of global oceans in every 24 hours with a swath width of 1800 km. In this study, both wind speed and directions are used for assimilation purpose. Unlike QuikSCAT, the KALPANA-1 provides the cloud motion vectors and water vapor winds within the atmospheric domain. In this study, both of these atmospheric motion vectors are used for the assimilation purpose.

To study the impact of 3DVAR technique during the recent cyclone PHYAN, the model is initialized at 0000 UTC 09 November 2009 and simulated for 72 hours. The resolution of the domain is taken as 27 km with 121 grid points along both the horizontal directions and the vertical

Table 2. Experiments carried out for the simulation of PHYAN

Experiment	Description/Specification
CONTROL	Uses same set of physics and dynamics as in the operational set up of India Meteorological Department and the initial and boundary conditions from FNL data
QSCAT	Uses same set of physics and dynamics as in the CONTROL experiment. The initial and boundary conditions are updated using the QuikScat derived winds.
K1CMV	Uses same set of physics and dynamics as in the CONTROL experiment. The initial and boundary conditions are updated using the KALPANA-1 derived cloud motion vectors.
K1WVW	Uses same set of physics and dynamics as in the CONTROL experiment. The initial and boundary conditions are updated using the KALPANA-1 derived water vapour winds.
QSCATK1	Uses same set of physics and dynamics as in the CONTROL experiment. The initial and boundary conditions are updated using the QuikScat as well as the KALPANA-1 derived winds.
SENKF	Uses same set of physics and dynamics as in the CONTROL experiment except the Kain-Fritsch scheme in place of Grell-Devenyi ensemble scheme. The initial and boundary conditions are same as that of CONTROL experiment.
SENBMJ	Uses same set of physics and dynamics as in the CONTROL experiment except the Betts-Miller-Janjic scheme in place of Grell-Devenyi ensemble scheme. The initial and boundary conditions are same as that of CONTROL experiment.
SENGR3D	Uses same set of physics and dynamics as in the CONTROL experiment except the Grell-3D scheme in place of Grell-Devenyi ensemble scheme. The initial and boundary conditions are same as that of CONTROL experiment.

resolution of the model contains 38 "η" levels (Table 1). At the top of the model grid, a constant pressure of 50 hpa is considered for all simulations. The central latitude and longitude for all of the experiments are taken as 16.5N and 74.0E respectively. The details of the model configurations and physics etc. are given in Table 1.

All of the experiments (Table 2) except that of SENKF, SENBMJ and SENGR3D consider same set of physics and dynamics for simulating the cyclone PHYAN. 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 (Dudhia, 1989; Hong *et al.,* 2004; Hong & Lim, 2006), Grell-Devenyi (G-D) ensemble cumulus convection scheme (Grell & 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 India Meteorological Department (IMD). The sensitivity experiment "SENKF" simulation considers Kain-Fritsch (KF) scheme (Kain & Fritsch, 1990,1993; Kain, 2004), the "SENBMJ" simulation considers Betts-Miller-Janjic (BMJ) scheme (Betts & Miller, 1986; Janjic, 2000) and the "SENGR3D" simulation considers Grell -3D cumulus parameterization (Grell & Devenyi, 2002) 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.

Results and discussions

The results obtained from eight sets of experiments (i.e. CONTROL, QSCAT, K1CMV, K1WVW, QSCATK1, SENKF, SENBMJ and SENGR3D) are discussed in this section. The assimilated mean sea level pressure and 850 hPa wind are compared with that of the CONTROL simulation. Further, the results from sensitivity experiments are also included in order to discuss the performance of the cumulus convection schemes. The

Fig 1(a-b). Kalpana-1 images of the tropical cyclone PHYAN at: (a) 1800 UTC November 10, 2009 and (b) 0700 UTC November 11, 2009.

(a) (b)

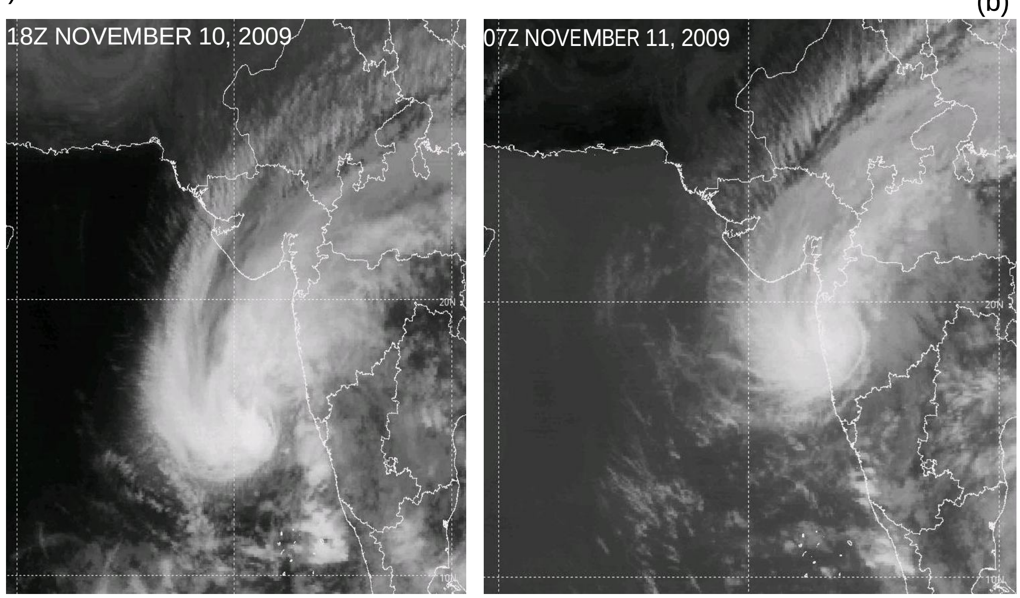

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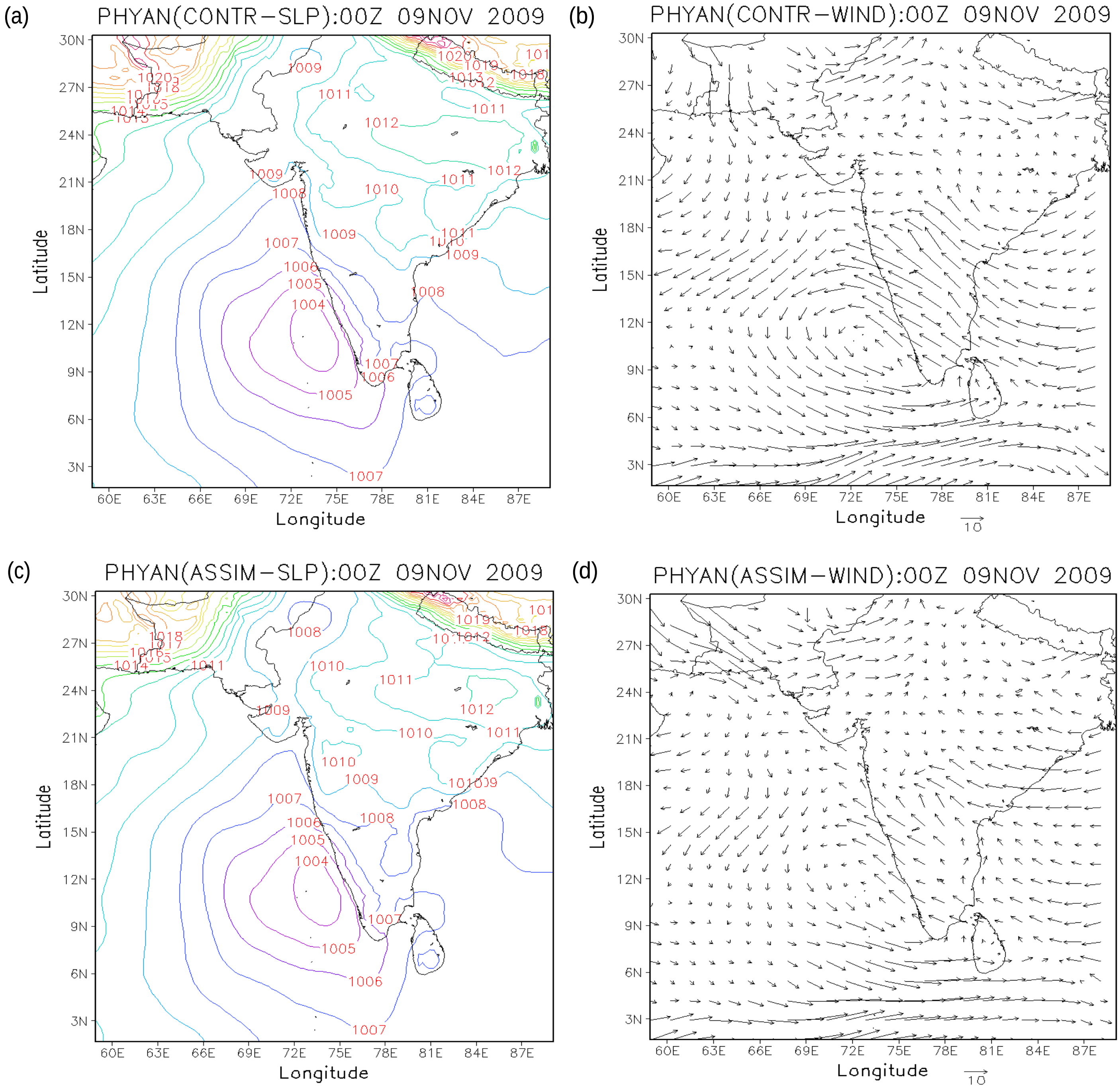
Fig 2(a-d): Initial conditions (at 0000 UTC 09 November 2009) for the simulation of the cyclone PHYAN: (a) mean sea level pressure (MSLP) from CONTROL run (b) surface wind from CONTROL run (c) MSLP from QSCAT run and (d) surface wind from QSCAT run.



discussions also include the comparison of the simulated tracks with that of the actual track of the cyclone to see the impact of the satellite derived winds from QuikSCAT and KALPANA-1 and the cumulus parameterization schemes.

A brief review of observed features of Phyan

Usually, the cyclonic storms in the Arabian Sea during the month of November are few in number. It may be noted that after such a type of storm in November, 1966, the tropical cyclone PHYAN developed in winter in the south-eastern Arabian Sea and swept northward along the eastern part of the Sea during 9-12 November 2009 until its land-fall at the north-west coast of India. The features of this cyclonic storm are analyzed using satellite measurements from KALPANA-1 and QuikSCAT. According to the IMD records, the low pressure formed over Kanyakumari on November 07, 2009 became well marked over Lakshadweep area during the next 24 hours being associated with the north-east monsoon surge. It then turned into a depression by November 09 noon and centered over the south-east and adjoining east central Arabian Sea (Joseph *et al.,* 2011). The depression then moved in the north/north-westerly direction till November 10, morning and re-curved towards north/north-east to form a deep depression; subsequently forming the cyclonic storm PHYAN by mid-night (Fig.1a). Continuing the movement, it finally crossed the west coast of India on November 11, at noon (Fig.1b) as it moved north-eastward with a speed ~ 20m/s (Joseph *et al.,* 2011).

The central pressure of this cyclonic system fell from 1000 hPa on November 09, afternoon to 988 hPa on November 11, noon. The maximum wind observed at the

Fig 3(a-d): Initial conditions (at 0000 UTC 09 November 2009) for the simulation of the cyclone PHYAN: (a) MSLP from K1CMV simulation (b) surface wind from K1CMV simulation (c) MSLP from K1WVW simulation and (d) surface wind from K1WVW simulation.

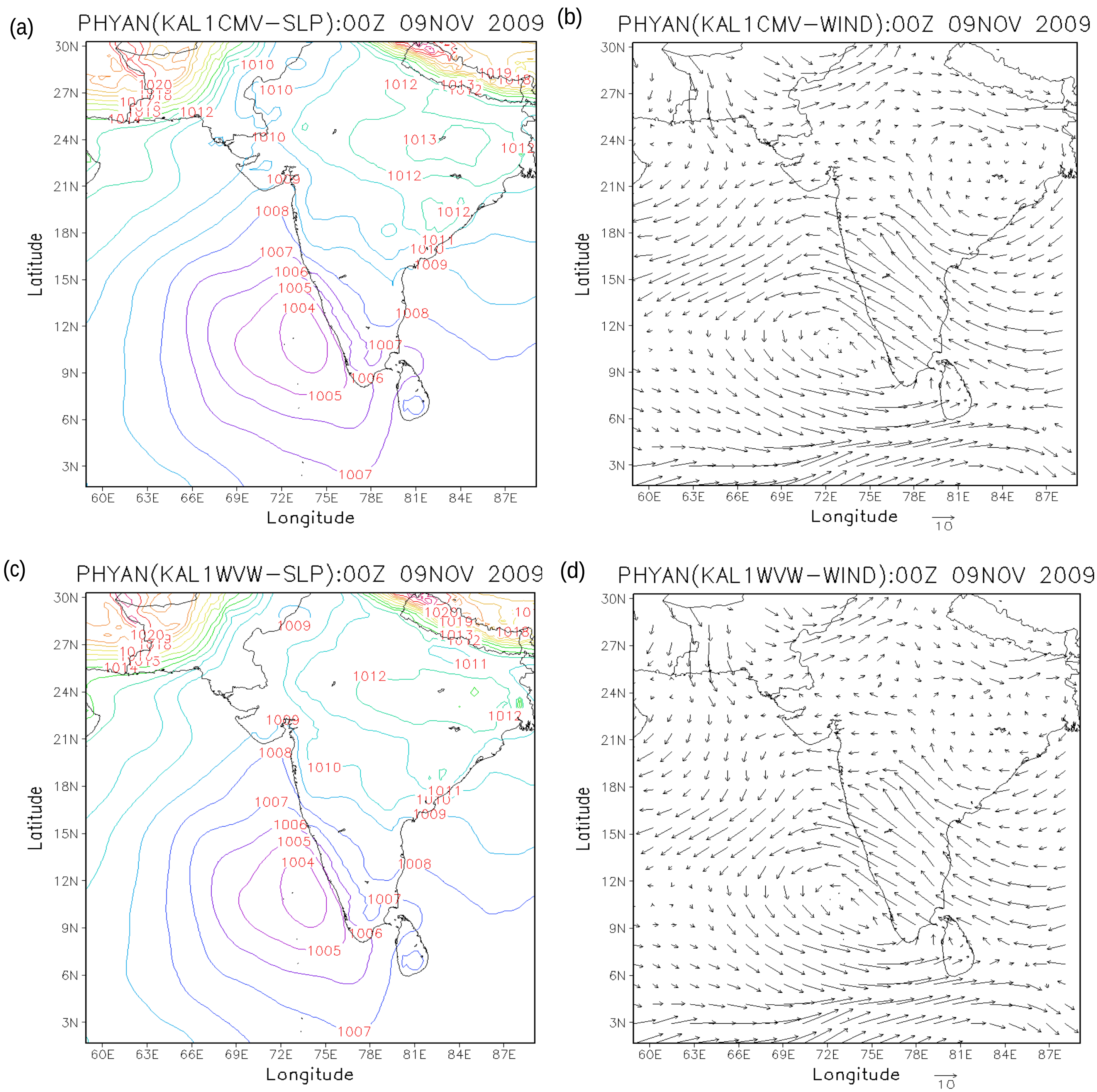


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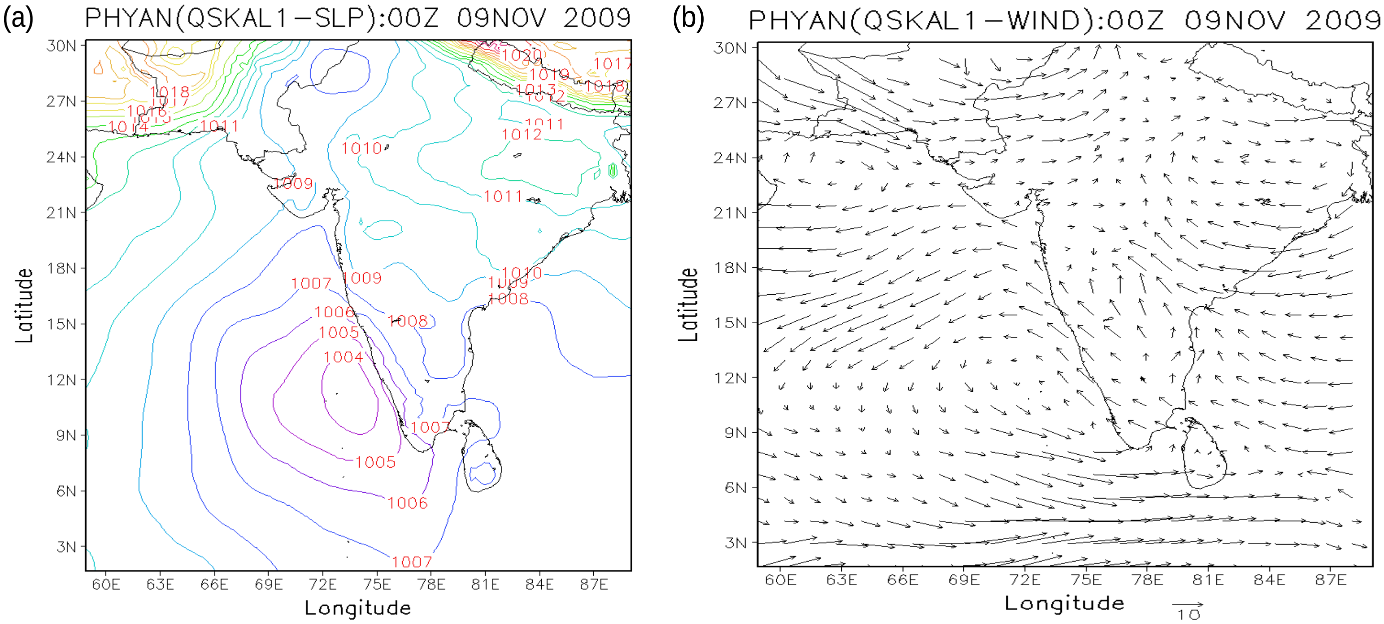
Fig 4(a-b): Initial conditions (at 0000 UTC 09 November 2009) for the simulation of the cyclone PHYAN: (a) MSLP from QSCATK1 simulation and (b) surface wind from QSCATK1 simulation.

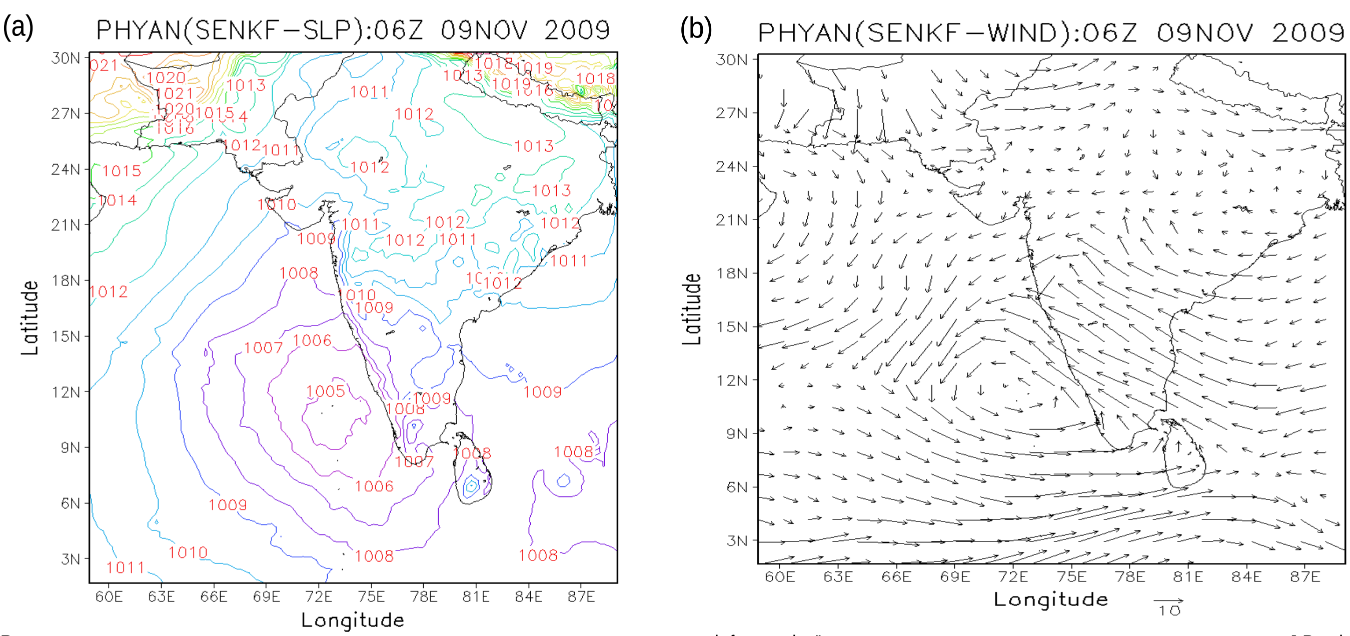


surface was ~ 23 m/s. Wide-spread rainfall and wind flow occurred over several places including Lakshadweep Islands, Kerala, Karnataka, Goa, Konkan, Madhya Maharashtra and south Gujarat region during the evolution and sustenance of the cyclonic storm.

The study of Singh and Singh (2011) based upon the satellite derived winds, indicates that the tropical cyclone started with a positive value of surface vorticity anomaly four days before the formation of depression which increased slightly later. One day prior to the formation of depression, the surface vorticity was maximum which subsequently decreased after the formation of depression on November 09.

The cyclonic storm caused several damages including the death of few fishermen, crop and property damages in Goa, Maharastra and Gujarat and disruption of transportation services even though the timely warning of IMD was issued. Though the loss of human resources, property, crops and human facilities were relatively less during the occurrence of the cyclonic storm, it is

Fig 5(a-b): Simulated mean sea level pressure (MSLP) and 850 hPa wind fields at 0600 UTC 09 November 2009 diuring the cyclone PHYAN: (a) MSLP from SENKF simulation and (b) 850 hPa wind from SENKF simulation.



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considered as one of the biggest natural hazards that hit the country in recent times.

Initial and boundary conditions

The initial conditions provided to the model from global analysis are shown in figures 2a-b and the updated initial condition from QSCAT simulation is shown in Fig. 2c-d. Similarly, the updated initial condition for K1CMV simulation is shown in figures 3a-b and for K1WVW in Fig. 3c-d. In the QSCATK1 simulation the model initial condition is shown in Fig.4. The boundary conditions in QSCAT, K1CMV, K1WVW and QSCATK1 experiments are also updated accordingly, using the satellite derived winds from QuikSCAT and KALPANA-1 geostationary satellites through 3DVAR technique within WRF modeling system. The initial and boundary conditions are same in the experiments SENKF, SENBMJ and SENGR3D as that of CONTROL simulation.

Variation of mean sea level pressure and 850 hPa wind fields

The mean sea level pressure (MSLP) and 850 hPa winds are shown in the Fig. 5-14. The Fig. 5-8 describe the pre-mature stage of the cyclonic storm PHYAN from various experiments at 0600 UTC on November 09, 2009. The center of the cyclone is not well defined at this hour from CONTROL simulation as well as from all the assimilation experiments QSCAT, K1CMV, K1WVW and QSCATK1 (figures not shown for brevity). However, all of the sensitivity experiments SENKF, SENBMJ and SENGR3D show a well-defined center at (11.5°N, 72.0°E), (11.5°N, 71.7°E) and (11.2°N, 72.3°E) respectively. If both the MSLP and 850 hPa wind fields are taken into account, then the center of the cyclone

Fig 6(a-d): Simulated mean sea level pressure (MSLP) and 850 hPa wind fields at 0600 UTC 09 November 2009 during the cyclone PHYAN: (a) MSLP from SENBMJ run, (b) 850 hPa wind from SENBMJ run, (c) MSLP from SENGR3D simulation and (d) 850 hPa wind from SENGR3D simulation

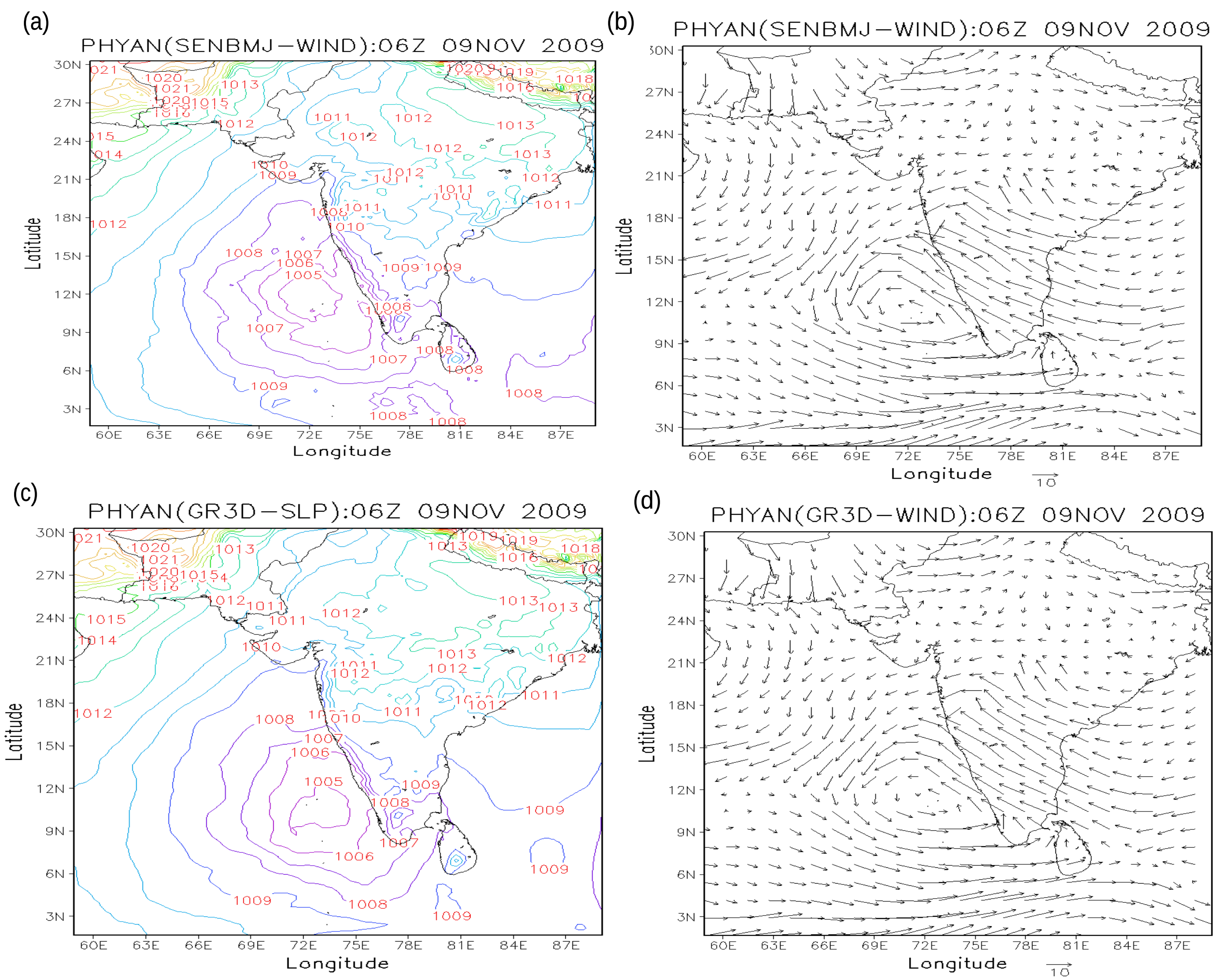
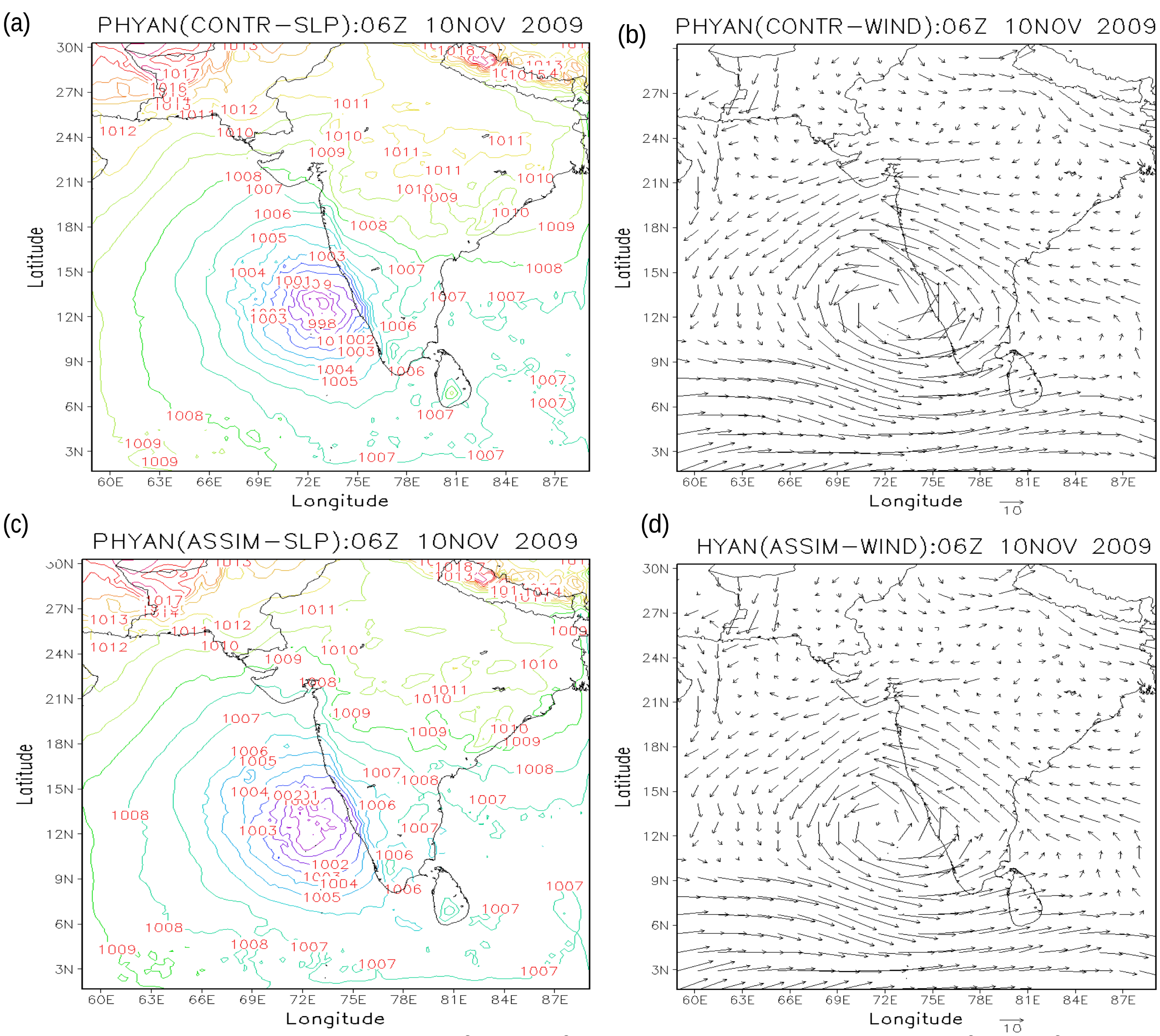


Fig 7(a-d): Simulated mean sea level pressure (MSLP) and 850 hPa wind fields at 0600 UTC 10 November 2009 diuring the cyclone PHYAN: (a) MSLP from CONTROL run, (b) 850 hPa wind from CONTROL run, (c) MSLP from QSCAT imulation and (d) 850 hPa wind from QSCAT simulation



from CONTROL simulation is at (11.4^{o}N, 72.3^{o}E). Similarly, the assimilation experiments QSCAT, K1CMV, K1WVW and QSCATK1 show the center of the cyclonic storm PHYAN at (11.0^{o}N, 73.2^{o}E), (11.6^{o}N, 71.6^{o}E), (11.5^{o}N, 72.1^{o}E) and (11.6^{o}N, 72.9^{o}E) respectively (figures not shown for brevity).

On November 10, the cyclone was in a progressive stage. Therefore, the 0600 UTC November 10 MSLP and 850 hPa wind fields represent the progressive and well developed cyclonic circulation off the west coast of India (Fig.7-10). The center of the cyclone is relatively well defined at this hour (Fig. 7-8, 9a-b) as compared to the 0600 UTC November 09 in CONTROL and assimilation experiments (figures not shown for brevity). The center of the cyclone according to the IMD observations/ predictions at this hour is (13.5^{o}N, 70.5^{o}E) based on the preliminary report on PHYAN (available at http://www.imd.gov.in/section/nhac/dynamic/cyclone.htm) . However, the simulated center from CONTROL run is (13.0^{o}N, 72.0^{o}E) with a significant error of ~55 km in latitudinal direction and ~165 km in longitudinal direction. In order to improve the model prediction, satellite derived winds from QuikSCAT and KALPANA-1 were used in the experiments QSCAT, K1CMV, K1WVW and QSCATK1 that predict the center of the cyclone at (13.0^{o}N, 71.8^{o}E), (12.6^{o}N, 71.4^{o}E), (13.2^{o}N, 72.4^{o}E) and (12.6^{o}N, 71.4^{o}E) indicating that the use of satellite derived winds do not show much improvement in predicting the center of the cyclone. However, the sensitivity experiments SENKF (Figure 9c-d), SENBMJ (Fig.10a-b) and SENGR3D

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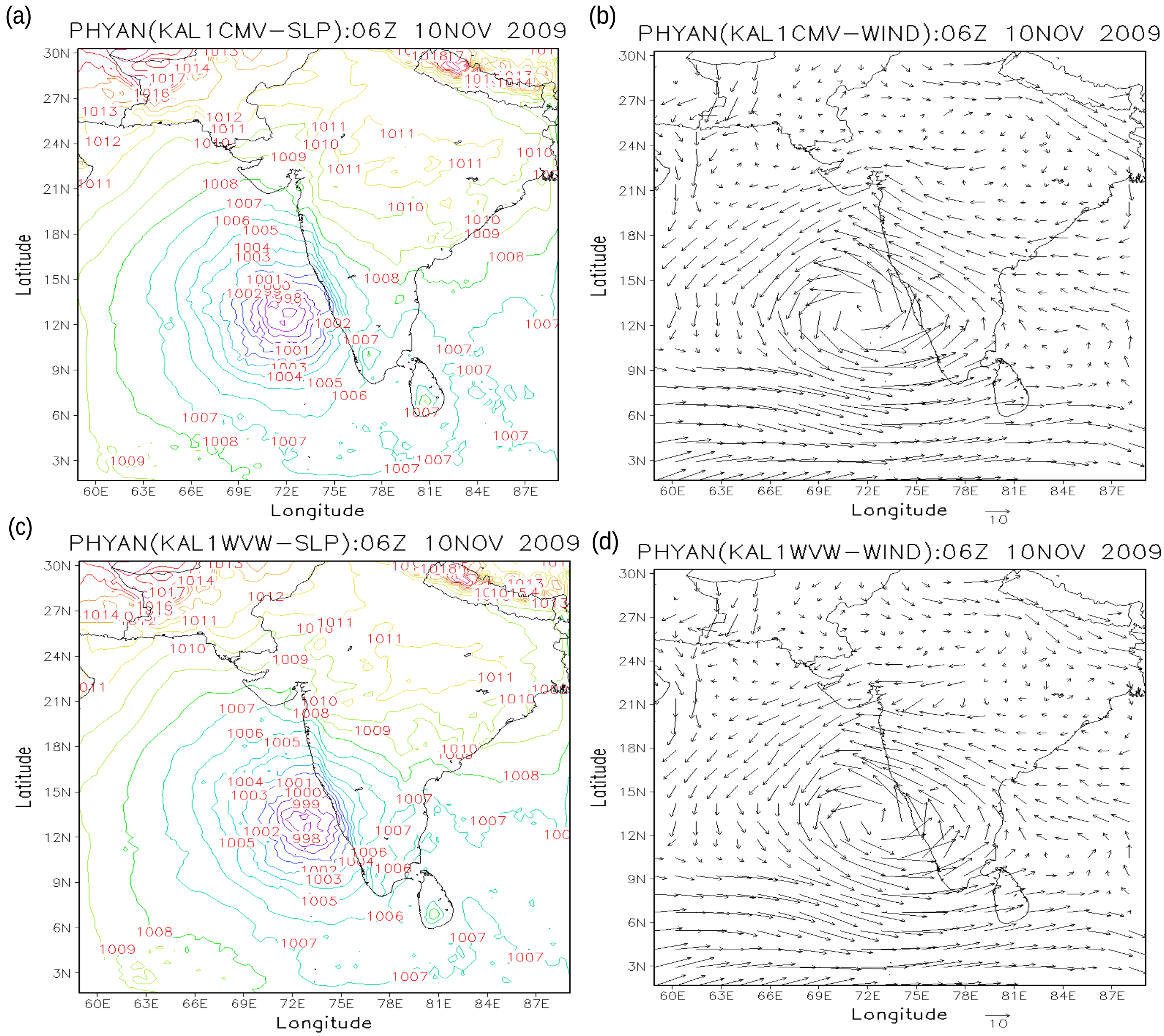
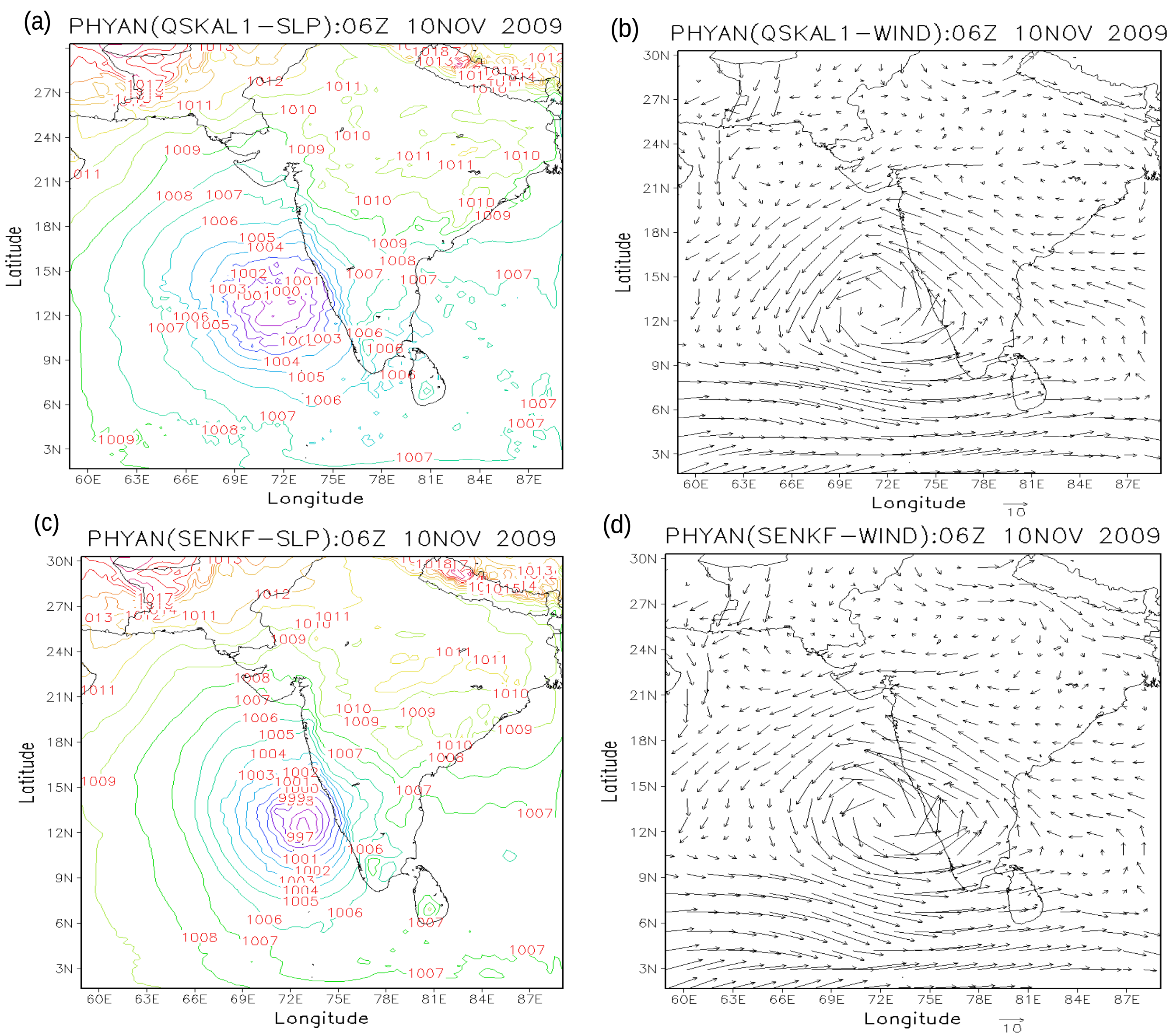
Fig 8(a-d): Simulated mean sea level pressure (MSLP) and 850 hPa wind fields at 0600 UTC 10 November 2009 diuring the cyclone PHYAN: (a) MSLP from K1CMV run, (b) 850 hPa wind from K1CMV run, (c) MSLP from K1WVW simulation and (d) 850 hPa wind from K1WVW simulation.



(Fig.10c-d) show a well-defined center at (12.6°N, 72.6°E), (14.1°N, 72.4°E) and (12.2°N, 71.9°E) respectively off the west coast of India, in the progressive stage of the cyclonic storm PHYAN and none of them indicate a significant improvement in the model prediction.

According to the IMD report on PHYAN, the cyclone was in the matured stage on November 11. Accordingly, the 0600 UTC MSLP and 850 hPa wind fields on November 11, 2009 is discussed here. The corresponding MSLP and 850 hPa wind fields from various simulations are shown in Fig.11-14. The IMD report on PHYAN indicates that the center of the cyclonic storm was at (17.5°N, 72.5°E). The CONTROL experiment also suggests a similar behaviour at this hour (Fig.11a-b) even though the center predicted is at (15.4°N, 72.9°E). Similar is the case from QSCAT experiment (Fig. 11c-d) which shows the center of the cyclone at (14.6°N, 73.1°E). However, the K1CMV experiment indicates that the cyclone is significantly away from the coast (Fig. 12a-b) with a very well-defined center at (14.7°N, 72.1°E). The K1WVW experiment suggests that the cyclonic storm is about to cross the west coast (Fig. 12c-d) with the center of the cyclone at (16.1°N, 72.9°E). The QSCATK1 experiment (Figure 13a-b) shows that the center of the cyclone was at (14.9°N, 72.4°E). All

Fig 9(a-d): Simulated mean sea level pressure (MSLP) and 850 hPa wind fields at 0600 UTC 10 November 2009 diuring the cyclone PHYAN: (a) MSLP from QSCATK1 run, (b) 850 hPa wind from QSCATK1 run, (c) MSLP from SENKF simulation and (d) 850 hPa wind from SENKF simulation



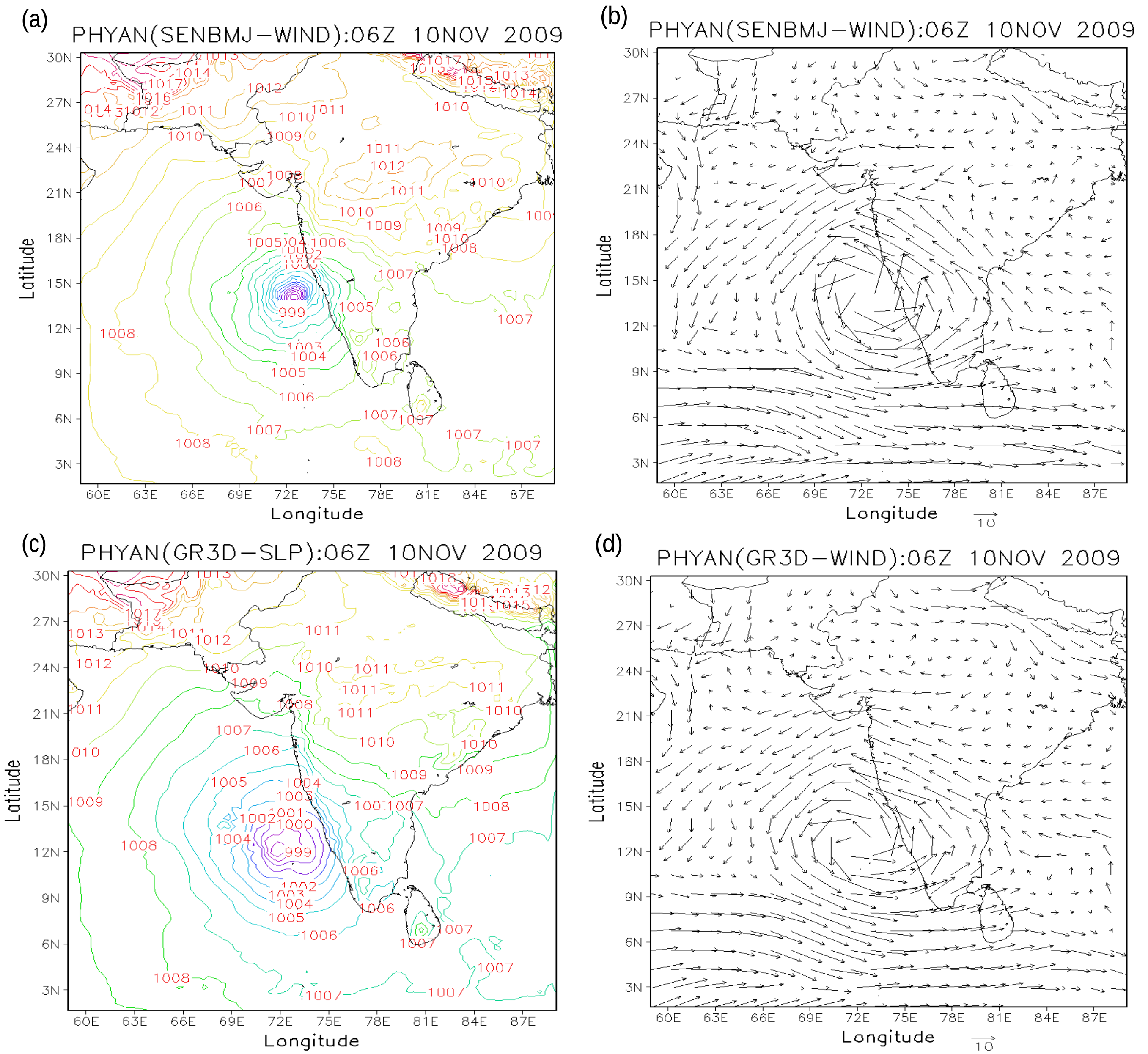
these experiments indicate that none of the assimilation experiments could improve the model prediction effectively. However, according to the IMD report the cyclone crossed the Maharashtra coast between Alibag and Mumbai between 1000 UTC and 1100 UTC on November 11, 2009. The sensitivity experiments SENKF, SENBMJ and SENGR3D predict the center of the cyclonic storm at (16.6^{o}N, 73.6^{o}E), (17.9^{o}N, 74.5^{o}E) and (15.1^{o}N, 73.4^{o}E) respectively. These results indicate that the cyclone is just going to cross the west coast at this hour in SENKF experiment (Figs 13c-d) whereas the storm has already crossed the west coast in SENBMJ experiment (Figs. 14 a-b) and it is about to cross the coast in SENGR3D experiment (Figs.14 c-d).

Track prediction

Accuracy in track prediction helps in avoiding the damages and serves as a life saving measure. Therefore, the efforts have been made in this direction by the researchers as well as operational community through numerical modeling and statistical approaches. Since, the models may not give a better track forecasting at times, the assimilation or sensitivity with respect to physical parameterization schemes especially the cumulus convection schemes may be helpful. In the present study the effort has been made in both the directions.

In order to predict the track of the cyclonic storm PHYAN, the center or eye of the cyclone is determined by considering the MSLP distribution and associated wind

Fig 10(a-d): Simulated mean sea level pressure (MSLP) and 850 hPa wind fields at 0600 UTC 10 November 2009 diuring the cyclone PHYAN: (a) MSLP from SENBMJ run, (b) 850 hPa wind from SENBMJ run, (c) MSLP from SENGR3D simulation and (d) 850 hPa wind from SENGR3D simulation.



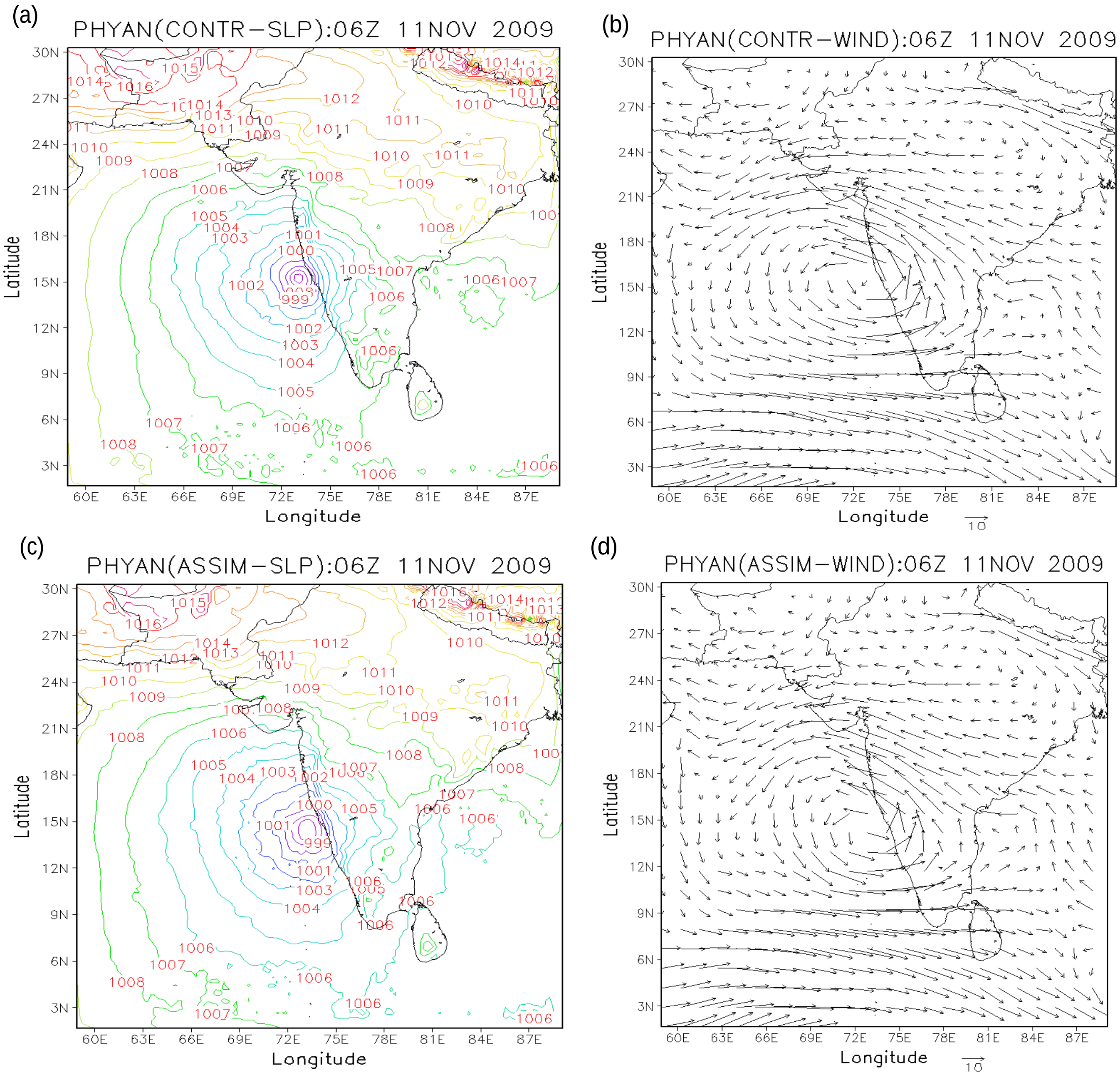
speeds. Ideally, a cyclone is a low pressure system and the center could easily be traced with the help of the surface pressure field. Further, the wind speed at the center of the cyclone should be minimum (zero is ideally for a supper cyclonic storm). Accordingly, the 850 hPa wind is considered for the determination of the center/eye of the cyclone along with the MSLP field. The track is drawn considering the available IMD observed/predicted values and the corresponding simulated positions of the centers of the cyclone.

The simulated as well as observed tracks (Fig.15) imply that both KF scheme and BMJ schemes perform better instead of G-D ensemble cumulus parameterization in predicting the track of the cyclonic storm PHYAN. However, there is a track error of ~100 km. It may be noted that none of the assimilation experiments show a significant improvement in the prediction of the track of the cyclone. It may be because of various reasons. There is no data for surface pressure fields and more number of observations is needed from the instruments like Doppler Weather Radar. Another reason could be the lack of better quality control mechanism.

Intensity of the cyclone

The intensity of a tropical cyclone is a measure of the level of damage in the coastal areas. Therefore, it is an

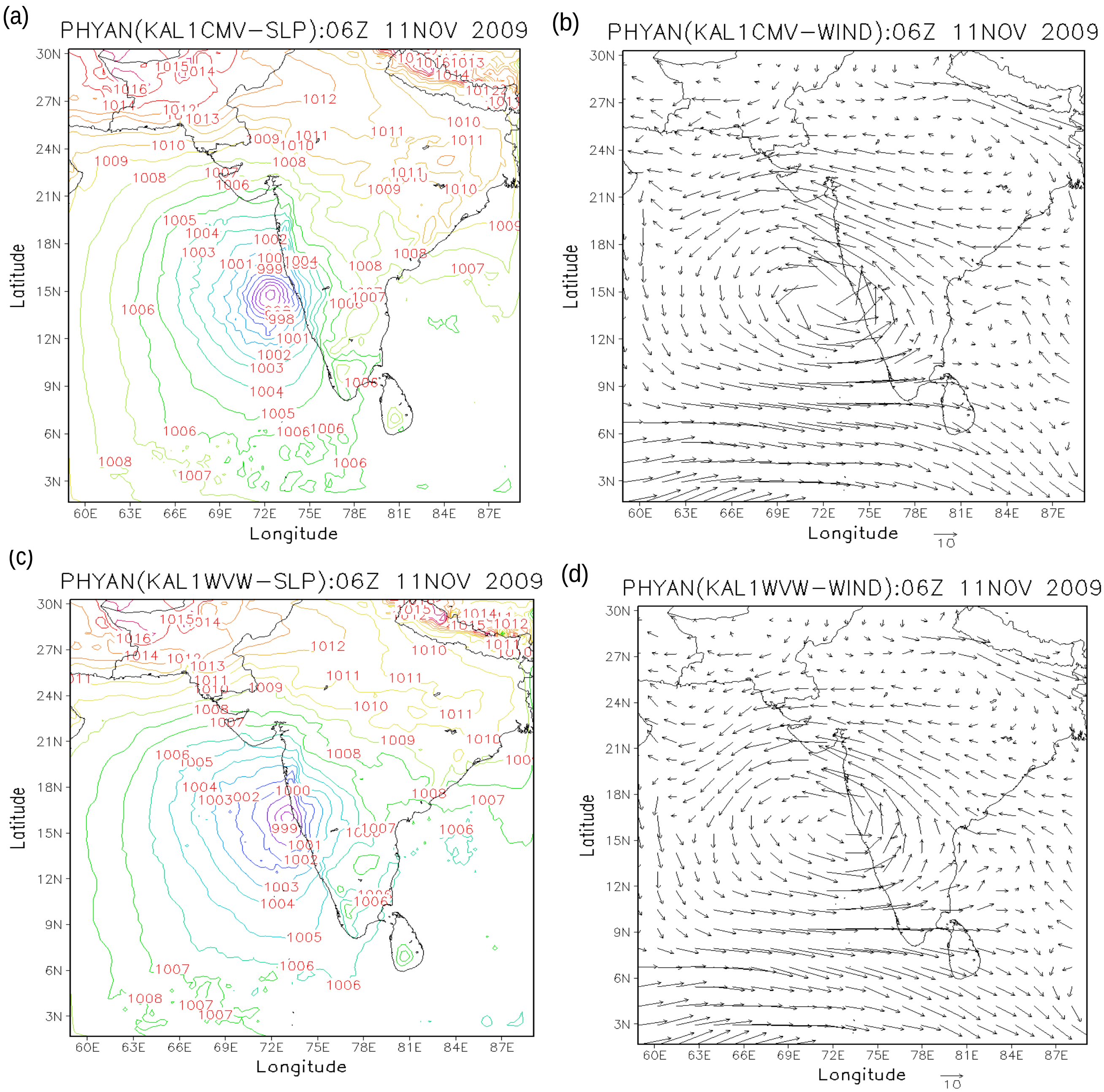
Fig 11(a-d): Simulated mean sea level pressure (MSLP) and 850 hPa wind fields at 0600 UTC 11 November 2009 diuring the cyclone PHYAN: (a) MSLP from CONTROL run, (b) 850 hPa wind from CONTROL run, (c) MSLP from QSCAT simulation and (d) 850 hPa wind from QSCAT simulation.



essential component of operational forecasting. For example, the extensive studies by Bhowmik *et al*. (2007) suggest an empirical model for the computation of the intensity of the tropical cyclones for operation purpose. Similarly, another study based on the tropical cyclone intensity by Bankert and Tag (2002) used an empirical method in terms of the central pressure for computation of maximum wind speed and hence the intensity of the tropical cyclones. Based on the earlier works (Misra & Gupta 1976), The intensity of tropical cyclones is usually calculated using the pressure difference between the center of the cyclone and its surroundings and the associated wind speeds and a number is assigned accordingly, which is known as “T-number” (T stands for tropical cyclone) or C. I. (cyclone intensity) number. It varies from 1.0 to 8.0 in 0.5 intervals (Table 3).

In order to calculate the T or C. I. number, the eye of the cyclone is determined first and the difference in the pressure between its center and surroundings is obtained in the present study. Accordingly, the T-number (or C. I. number) is assigned to the cyclone by considering the existing guidelines of IMD (available at

Fig 12(a-d): Simulated mean sea level pressure (MSLP) and 850 hPa wind fields at 0600 UTC 11 November 2009 diuring the cyclone PHYAN: (a) MSLP from K1CMV run, (b) 850 hPa wind from K1CMV run, (c) MSLP from K1WVW simulation and (d) 850 hPa wind from K1WVW simulation.



http://www.imd.gov.in/section/nhac/dynamic/faq/FAQP.htm). This procedure is followed for each calculation done at three hour intervals for all the simulations carried out in this study. However, the comparison is shown here at those hours where the IMD observations are available.

The intensity of the cyclone with various simulations is given in the Table 3. The simulated results are compared with the IMD predicted results. It is evident that the K1CMV experiment performs better as far as assimilation of satellite derived winds is concerned. Out of the three sensitivity experiments, SENBMJ and SENKF perform better in predicting the intensity of the cyclone as when compared with the actual intensity and the CONTROL simulation.

The satellite image at 0600 UTC on November 10, 2009 (Figure not shown for brevity) agrees qualitatively with the simulated results (Fig. 8-11). According to the KALPANA-1 satellite observations, the cyclonic system was a deep depression with intensity T 2.0 at 0600 UTC. From November 10th onwards, the system moved nearly northward. It then moved north to northeastward on November 11, 2009 and intensified to T 2.5 at 0600 UTC

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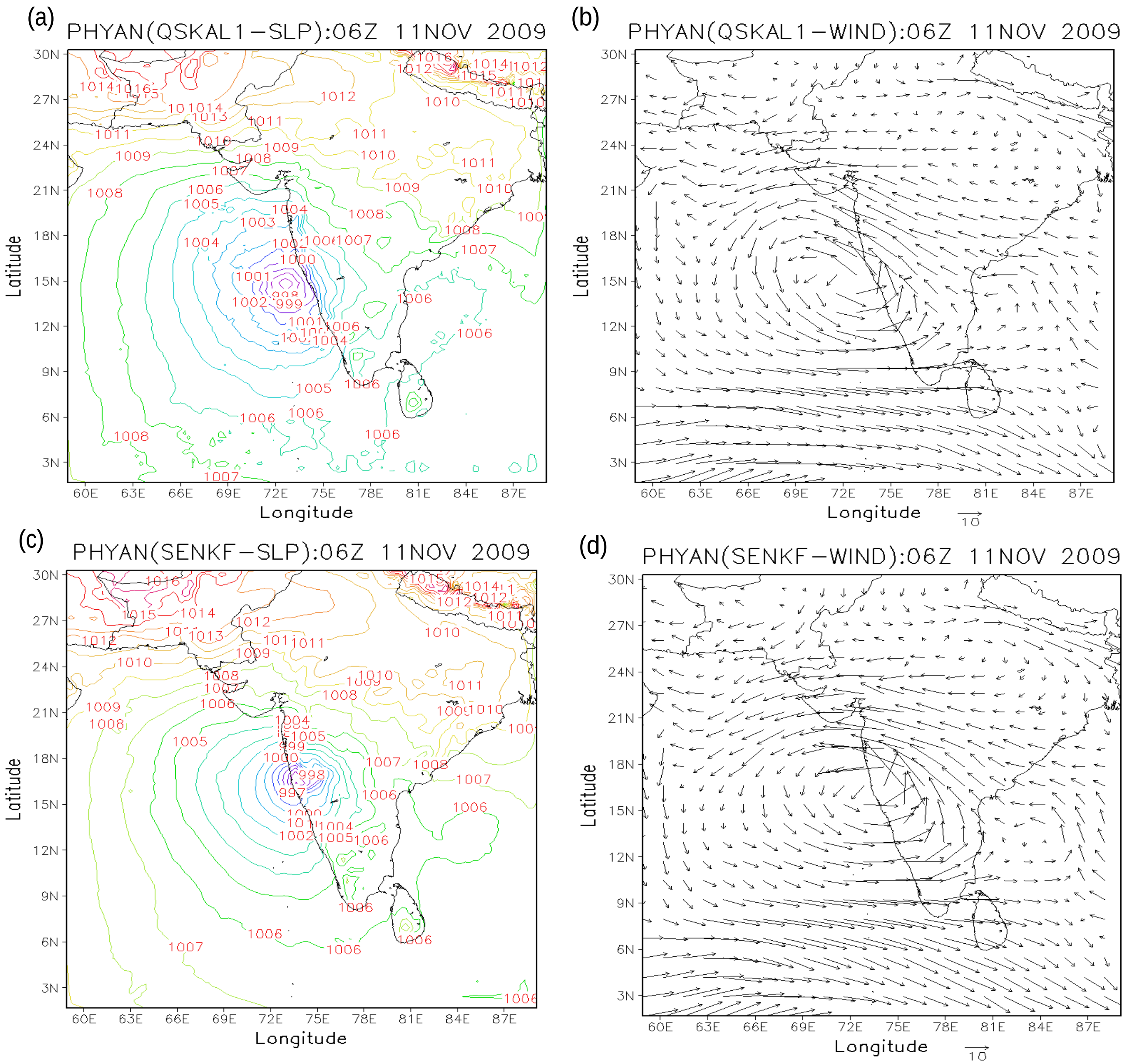
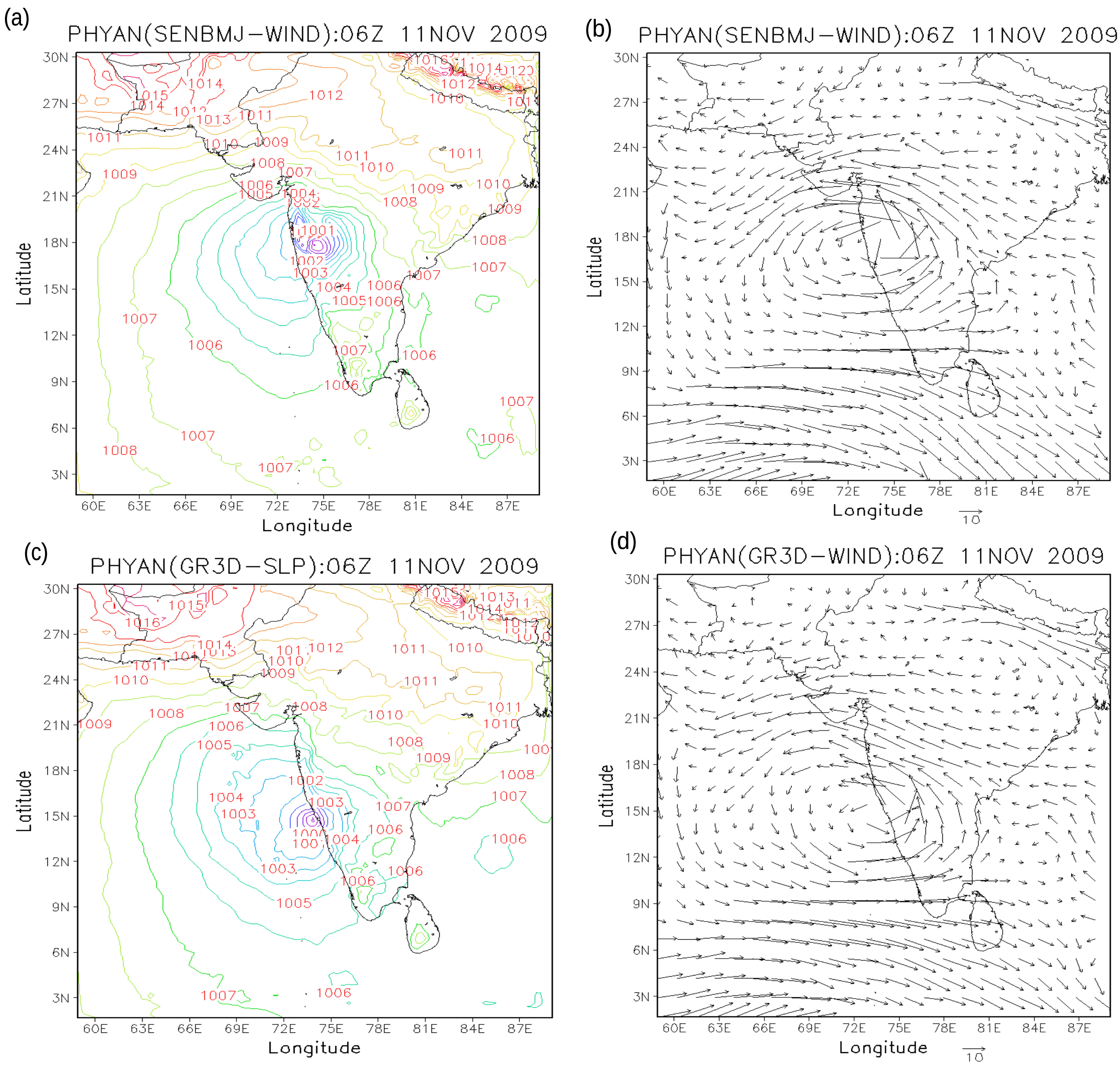
Fig 13(a-d): Simulated mean sea level pressure (MSLP) and 850 hPa wind fields at 0600 UTC 11 November 2009 diuring the cyclone PHYAN: (a) MSLP from QSCATK1 run, (b) 850 hPa wind from QSCATK1 run, (c) MSLP from SENKF simulation and (d) 850 hPa wind from SENKF simulation.



to a cyclonic storm. Similar results are also obtained from the model simulations. According to the satellite observations, the curved band pattern of the cyclone was replaced with central dense overcast (CDO) pattern in the early morning of November 11. However, the system slightly weakened from 0600 UTC November 11, as it came close to the coast due to northeastward movement. The CDO pattern disorganized and curved band pattern reappeared. It made landfall with intensity of T 2.5. However, the simulated results from CONTROL and assimilation experiments do not show any land-fall even though the SENKF and SENBMJ experiments show land-fall.

The statistical measures (Table 4) such as root mean square error (RMSE) and fractional bias (FB) are computed using the available IMD observed/predicted values of T-numbers and the corresponding simulated results from various experiments. The RMSE is lower (i. e. 0.2041) in case of QSCATK1 experiment as compared to that of CONTROL, QSCAT, K1CMV and K1WVW experiments indicating that the combination of surface and upper air winds results in better model predicted intensity during the simulation of PHYAN. All of the assimilation experiments show a positive fractional bias except K1CMV which shows a negative FB value similar to that of the CONTROL experiment.

Fig 14(a-d): Simulated mean sea level pressure (MSLP) and 850 hPa wind fields at 0600 UTC 11 November 2009 diuring the cyclone PHYAN: (a) MSLP from SENBMJ run, (b) 850 hPa wind from SENBMJ run, (c) MSLP from SENGR3D simulation and (d) 850 hPa wind from SENGR3D simulation.



The behavior of the model based on the RMSE values is similar to those based on the normalized mean square error (NMSE) values. Therefore, the NMSE values are not depicted for sake of brevity. In view of this, the student's t-test for significance testing is carried out based on the bootstrap re-sampling technique (Chang and Hanna, 2004) in order to examine the hypothesis that the differences between the values of NMSE and FB in CONTROL and assimilation experiments (i.e. QSCAT, K1CMV, K1WVW and QSCATK1) are significantly different from zero at 95% confidence interval. The significance test (Table 5) implies that the differences in NMSE values of assimilation experiments with respect to the CONTROL experiment are not significantly different from zero at 95% confidence interval for T-number calculation except that of K1CMV. The opposite result for FB is obtained as compared to that of NMSE from significant testing (Table 5).

Summary and conclusion

The primary objective of the present study is to examine the impact of the satellite derived winds from QuikSCAT and KALPANA-1 on the prediction of the

Table 3. Comparison of T. No. from IMD prediction and model simulations

Date	Time	IMD	CONT-ROL	QSCAT	K1CMV	K1WVW	QSCA-TK1	SENKF	SEN-BMJ	SEN-GR3D
09/11/09	0900	1.5	-	-	-	-	-	1.0	1.5	1.0
	1200	1.5	1.5	-	1.5	1.0	-	1.5	1.5	1.5
	1800	1.5	2.0	1.0	1.5	1.0	1.0	1.5	1.5	1.5
10/11/09	0000	1.5	2.5	1.5	2.0	1.5	1.5	2.0	1.5	2.0
	0300	2.0	2.5	2.0	2.5	1.5	2.0	2.0	2.0	2.0
	0600	2.0	2.5	2.0	2.5	2.0	2.0	2.0	2.5	2.0
	1200	2.0	2.5	2.0	2.5	2.0	2.0	2.0	2.5	2.0
	1800	2.5	2.5	2.0	2.5	2.5	2.5	2.5	3.0	2.5
	2100	2.5	3.0	2.5	2.5	2.5	2.5	3.0	2.5	2.5
11/11/09	0000	2.5	3.0	2.5	3.0	2.5	2.5	3.0	2.0	2.5
	0300	3.0	2.5	2.0	2.5	2.0	2.5	3.0	2.0	2.5
	0600	3.0	2.5	2.0	2.5	2.0	2.0	2.5	2.0	2.0
	0900	2.5	2.0	2.0	2.5	2.0	2.0	2.5	1.5	2.0

Fig 15: Observed and simulated track of PHYAN.

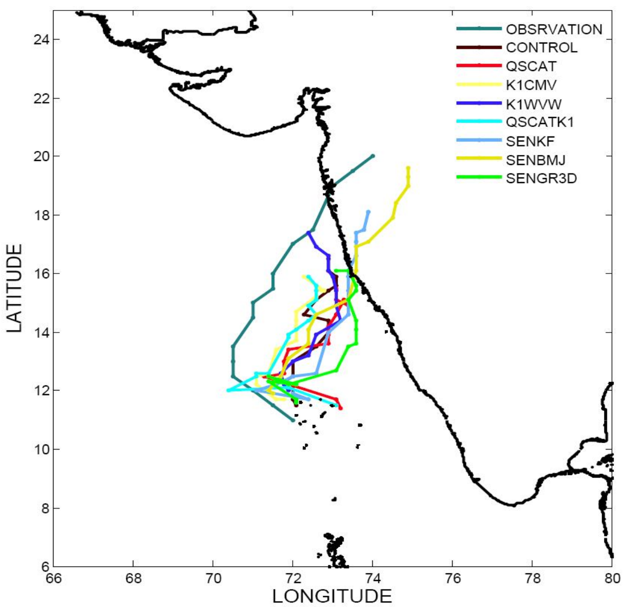


Table 4. Statistical measures for the T-number calculation (measure of intensity

Name of the Experiment	Root Mean Square Error (RMSE) values	Fractional Bias (FB) values
CONTROL	0.5774	-0.2308
QSCAT	0.2887	0.0909
K1CMV	0.4082	-0.1600
K1WVW	0.2887	0.0909
QSCATK1	0.2041	0.0444

cyclonic storm PHYAN. For this purpose, four sets of experiments such as QSCAT (considering the surface winds from QuikSCAT), K1CMV (considering the cloud motion vectors from KALPANA-1), K1WVW (considering the water vapour winds from KALPANA-1) and QSCATK1 (considering both the surface winds from QuikSCAT and atmospheric motion vectors from KALPANA-1) are designed in addition to the CONTROL simulation. In all of these experiments same set of physics and dynamics is used keeping in view of the operational set up of IMD. Further, three sensitivity experiments such as SENKF, SENBMJ and SENGR3D are designed in order to examine the influence of cumulus convection parameterizations (i.e. KF, BMJ and Grell-3D schemes) available in WRF modeling system version 3.1. For this purpose, the mean sea level pressure and 850 hPa wind fields are analyzed by comparing with the available satellite observations. In addition, the track of the cyclone PHYAN is drawn from the eight experiments and compared with the actual observed track.

The qualitative analysis suggests that the use of CMV for updating the initial and boundary conditions in WRF modeling system seems to be reasonably useful in predicting the intensity of the cyclone PHYAN. On the other hand, the quantitative analysis indicates that the consideration of the atmospheric motion vectors (from KALPANA-1) along with the QuikSCAT sea surface winds in the three dimensional variational assimilation procedure to update the model initial and boundary conditions turns out to be more effective. However, an extensive study is still required in this direction. A qualitative analysis shows that the BMJ and KF cumulus convection parameterizations perform relatively better as compared to G-D ensemble cumulus scheme, in simulating the track and intensity of the cyclone PHYAN respectively. The statistical significance testing for intensity or T-number implies that the statistical measures like NMSE and FB behave in a complementary manner while considering their differences at 95% confidence intervals for assimilation experiments with respect to the CONTROL simulation.

The present study is the first attempt in utilizing the KALPANA-1 derived winds for assimilation purpose. On the other hand a significant number of studies are available using QuikSCAT winds. However, our future studies would consider a number of cases in order to

Table 5. Results of significance testing to determine whether the difference in normalized mean square error (NMSE) and FB values between the CONTROL and assimilation experiments (i.e. QSCAT, K1CMV, K1WVW and QSCATK1) is significantly different from zero for T-numbers. An 'x' indicates that the results are significant at 95 % confidence intervals

Statistical measures	QSCAT	K1CMV	K1WVW	QSCATK1
NMSE		x		
FB	x		x	x

bring out a better understanding regarding the utility and impact of the satellite derived winds in predicting tropical cyclone tracks and intensity.

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