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Impact of satellite derived wind in mesoscale simulation of Orissa super cyclone

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Prediction of track and intensity of tropical cyclones is one of the most challenging problems in numerical weather prediction (NWP). Providing reasonably accurate initial condition to tropical cyclone forecast models has always been a problem to numerical weather forecasters. Recent advancements in spatial resolution and radiometric sensitivity have significantly improved the accuracy and density of satellite derived wind. The objective of the present study is to examine the impact of satellite derived winds in improving model initial condition and hence in mesoscale simulation of cyclonic storm. In this study, PSU/NCAR mesoscale model MM5 is used to produce 5-day simulation of the super cyclone that crossed Orissa coast on 29 October 1999. Winds derived from QSCAT, SSM/I, MSMR and METEOSAT-5 satellites are used in preparation of high-resolution reanalysis (HRR) and improving model initial condition. The strength of the southwesterly wind (over ocean) converging to the storm is found to be stronger both in the HRR and improved model initial condition compared to that in the NCEP/NCAR reanalysis. The strength of the cyclonic vortex is also better represented in the HRR and improved model initial condition. Improvement in model initial condition has resulted in consistent and significant improvement (35% in average) in prediction of the track of the storm.

[**Key words:** Cyclone, mesoscale, satellite derived wind, high-resolution reanalysis, super cyclone, Orissa cyclone]

Introduction

Bay of Bengal is potentially energetic for the development of cyclonic storms. These storms, in particular, the post-monsoon storms that cross the coastal states of India and Bangladesh are highly devastating, causing loss of life and huge damages to property. Therefore, reasonably accurate prediction of the Bay of Bengal cyclones is of great importance to avoid or reduce the loss of life and damages to property.

The sparsity of observations, both near the center of the storm and in the surrounding environment is a major constraint to the accuracy of the tropical cyclone forecast[1,2]. Several studies[3,4] have demonstrated that the inclusion of near-storm observations can improve the forecast skill of the models substantially.

The satellite derived wind has long been recognized as an important observation for tropical cyclone analysis and forecasting. Since then, wind derived from cloud motion in the infrared and visible imagery obtained from meteorological satellites has been routinely used in numerical weather prediction. During 1980s' use of water vapor imagery in estimation of wind vector was initiated and a number of studies[5-8] in the subsequent years indicated their utility in numerical prediction of tropical cyclone. Although, satellite derived wind is in use in numerical weather prediction for more than two decades now, the recent advancement in spatial resolution and radiometric sensitivity have significantly improved the accuracy and density of the wind products[9]. The high-density satellite wind available over large tropical region is very useful in tropical cyclone research[10-12]. Leslie *et al.*[12] demonstrated that the high-resolution simulation of tropical cyclones can be significantly improved with the assimilation of high-density satellite winds. Goerss *et al.*[13] examined the sensitivity of high-density winds from Geo-stationary Operational Environmental Satellites (GOES) on the forecast skill of NOGAPS (Navy Operational Global Atmospheric Prediction System) model. The results indicate 12-14% improvement in hurricane track forecast.

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In India, though a number of attempts have been made towards improving model initial condition using satellite derived meteorological parameters; they are mostly on simulation/prediction of monsoon systems using global models[14-17]. Rizvi *et al.*[16] have shown that the inclusion of MSMR surface wind speed has increased the strength of the easterlies over the tropical Indian Ocean. Das Gupta *et al.*[17] showed that the low level trade wind and sub-tropical anti-cyclone are strengthened with the inclusion of METEOSAT data along with other conventional and non-conventional datasets. The impact is more pronounced over oceanic region. There are few studies towards the use of satellite-derived parameters in simulation of the Bay of Bengal cyclones. Bansal *et al.*[18] used ERS-1 scatterometer wind in analysis and prediction of a Bay of Bengal storm. Roy Bhowmik & Sud[19] have studied the impact of MSMR surface wind on surface wind analysis in development and mature stage of tropical cyclones. Recently Kar *et al.*[20] investigated the sensitivity of satellite products towards global (T80) simulation of Orissa super cyclone.

In the present study, PSU/NCAR mesoscale model MM5 (Dudhia[21]) is used to simulate the super cyclonic storm that crossed Orissa coast on 29 October 1999 and caused devastation in 12 coastal districts of the state. The model has already showed some skill in simulating hurricanes[22], particularly, at high resolutions[23] and has also been tested for simulation of the Bay of Bengal cyclones[24,25]. The objective of the present study is to improve the model initial condition using satellite-derived wind and its subsequent impact in mesoscale simulation of Orissa super cyclone.

Methodology

Synoptic situation

The cyclonic storm of 29 October 1999 was the most intense storm in the history of Orissa with 12 coastal districts of the state battered by winds reaching 250 km/hr. The fury of wind continued for more than 36 hours and wind of 55 km/hr or more continued almost for three days. More than 50 cm of rainfall was recorded in 3 days (29-31 October 1999) at some of the places that led to devastating floods. The storm caused huge damage to property and nearly 10,000 people lost their lives.

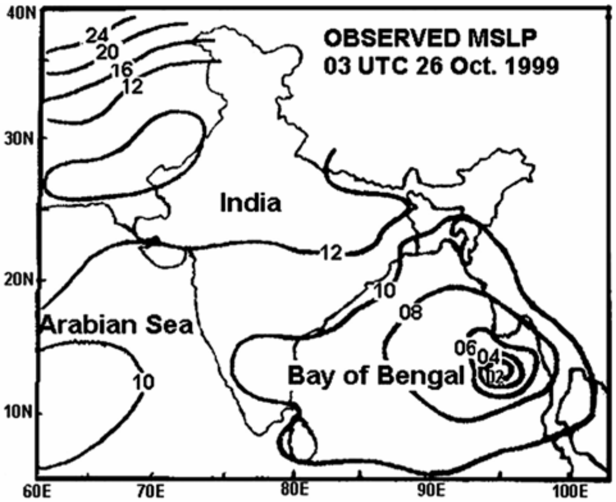

Fig. 1 — Mean sea level pressure (in hPa) chart valid at 03:00 UTC 26 October 1999

The initial vortex of the storm was observed over the gulf of Thailand at 00:00 24 October 1999 and believed to be remnant of the tropical cyclone 'TS992EVE' over the South China Sea. Moving westward across Malaysian Peninsula, it emerged in north Andaman Sea as a well-marked low-pressure area at 00:00 UTC 25 October. It intensified into a deep depression by 12:00 UTC of the same day and located near 12.5°N/98.0°E. Moving in west northwesterly direction it intensified into a cyclonic storm by 03:00 UTC 26 October and centered at 13.5°N/95.0°E. The mean sea level pressure chart (Fig. 1) shows the storm with central SLP of 1002 hPa with three closely following isobars indicating the pressure gradient. The satellite picture of the storm shows curved cloud bands coiled around the storm (figure not shown) indicating intensifying storm. Thereafter, the storm moved northwestward and intensified into a severe cyclonic storm (central pressure 992 hPa) by 03:00 UTC 27 October. The storm reached its peak intensity at 18:00 UTC 28 October (with central pressure 912 hPa) and continued to move in the same direction till landfall at 05:30 UTC 29 October around 50 km south of Paradip on Orissa coast (Fig. 2).

After landfall, the storm remained practically stationary around 20.5°N/86.0°E (close to Bhubaneswar) for almost 42 hours. It maintained cyclonic intensity almost up to 12:00 UTC 30 October. By morning of 31 October the storm returned into the Ocean (figure not shown). At this stage it came under the influence of mid-tropospheric flow that caused southward drifting of the storm into the Ocean. The observed track (along with the strength) of the storm during its life span is shown in Fig. 3.

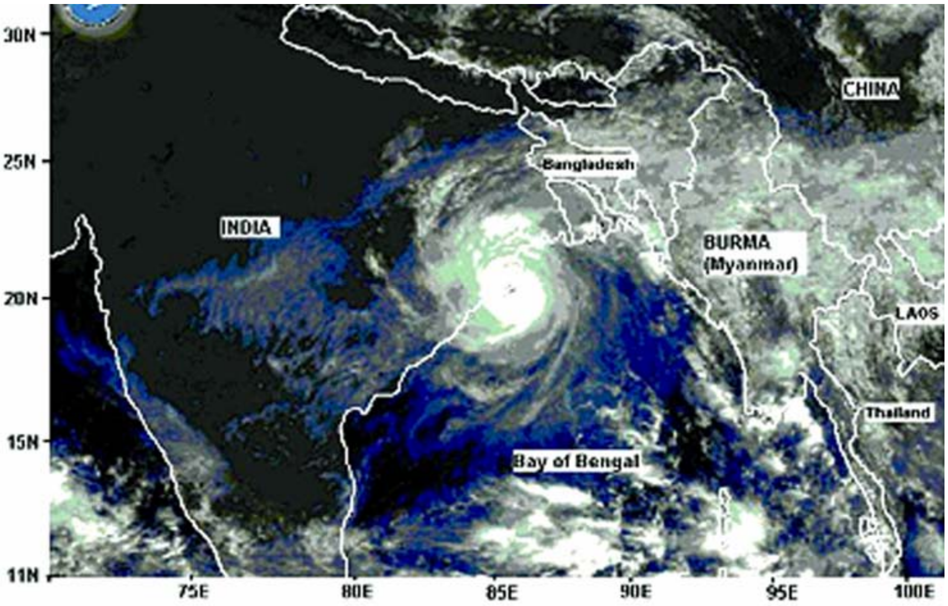

Fig. 2—Satellite pictures of the storm as obtained from EUMETSAT METEOSAT at 05:30 UTC 29 October 1999

The model

The mesoscale model MM5 developed at National Center for Atmospheric Research (NCAR) and Penn State University is used in simulating the storm. This is a very sophisticated and versatile community model widely used in simulation/prediction of global to storm scale weather systems around the world. MM5 is a hydrostatic/nonhydrostatic primitive equation model with model equations written in surface pressure weighted flux form in terrain following sigma coordinate. The details of the model are provided in Dudhia[21] and Grell *et al.*[26]. The model configuration used in the present study (Table 1) is based on extensive sensitivity studies by Mandal *et al.*[25]

Satellite data used

A number of satellites (both polar orbiting and geo-stationary) providing wind speed/vector were active during the period of Orissa super cyclone. In the present study, the wind speed at ocean surface obtained form Special Sensor Microwave Imager (SSM/I, at 0.25° resolutions) on board on the Defense Meteorological Satellite Project (DMSP) and Multi-frequency Scanning Microwave Radiometer (MSMR, at 0.75° resolutions) on board Indian Remote Sensing Satellite (Oceansat-I) are utilized. In addition, the wind vector at ocean surface obtained from microwave scatterometer on board on QuikBird satellite known as QSCAT and Cloud Motion Vector (CMV) from METEOSAT-5 (63°E) are also used in the preparation of high resolution (30 km) reanalysis (HRR) and hence in improving the model initial condition.

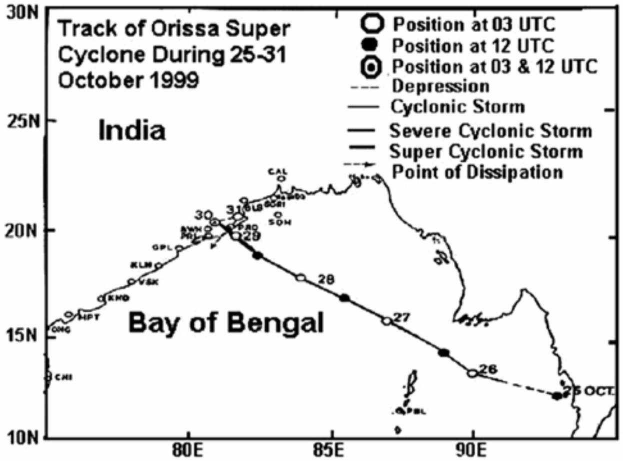

Fig. 3—The observed track of the storm with strength during the period 25 October to 1 November 1999

Ocean surface wind speed from SSM/I is shown in Fig. 4. This shows that the satellite has provided the much-needed observations over the data sparse oceans for the preparation of HRR though there was no observation close to the storm center. The wind vector at ocean surface from QSCAT shows that there were some observations in the vicinity of the storm at 12:00 UTC 25 October 1999, (figure not shown) though the circulation pattern was little noisy. There was no observation over the Bay of Bengal at other

Table 1 — Overview of the MM5 model used in the present study

Dynamics	Hydrostatic/Nonhydrostatic
Model Domain	10°S-31°N, 58°E-110°E
Horizontal grid distance	90 km; 60 km; 30 km
Integration time step	180 sec.; 120 sec; 60 sec
Map projection	Mercator
Horizontal grid system	Arakawa B-grid
Vertical co-ordinate	Terrain-following sigma co-ordinate 23 sigma levels (7 within boundary layer)
Time integration scheme	Leapfrog scheme (with time split technique)
Spatial differencing scheme	2nd order centered
Lateral Boundary condition	Time and inflow/outflow dependent (Hydrostatic)/relaxation (non-hydrostatic)
Top boundary condition	Rigid Lid (non-hydrostatic)
Radiation parameterization	NCAR CCM2 radiation scheme
Surface layer parameterization	Multi-layer soil model
Cumulus parameterization	Grell
PBL parameterization	NCEP MRF
Microphysics	Hsie's warm rain scheme

two times (18:00 UTC 25 & 00:00 UTC 26 October). Figure 5 shows the coverage of MSMR data at 18:00 UTC 25 October 1999 (There was no observations available at 12:00 UTC 25 and 00:00 UTC 26 October over the model domain). The coverage of cloud motion vector from METEOSAT-5 is shown in Fig. 6. The observations were mostly in the upper troposphere (between 250-100 hPa).

Experimental design

Two numerical experiments are conducted to examine the impact of satellite-derived winds in MM5 simulation. The model is integrated up to 123 hours producing 5 days forecast of the storm. In the first experiment, the model initial and boundary conditions are provided from NCEP/NCAR reanalysis (2.5° × 2.5° resolution) interpolated to model grids (30 km resolution). The large-scale reanalysis from NCEP/NCAR is of coarse resolution and shows the storm to be very weak and spreaded over a larger area as compared to the observed one. As simple interpolation of coarse resolution datasets into

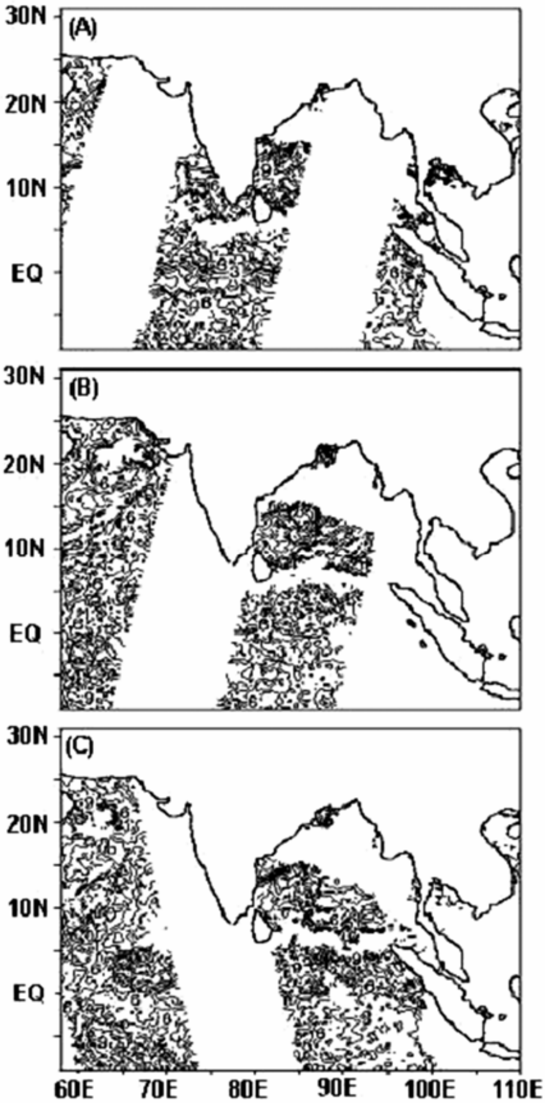

Fig. 4 — SSM/I ocean surface wind utilized in preparation of HRR at (A) 12:00 UTC 25 October, (B) 18:00 UTC 25 October, (C) 00:00 UTC 26 October 1999

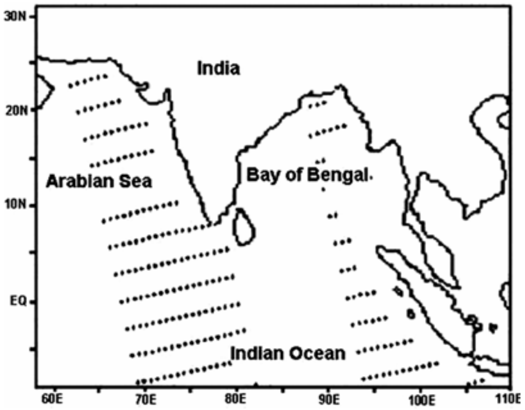

Fig. 5 — MSMR data coverage over the region at 18:00 UTC 25 October 1999

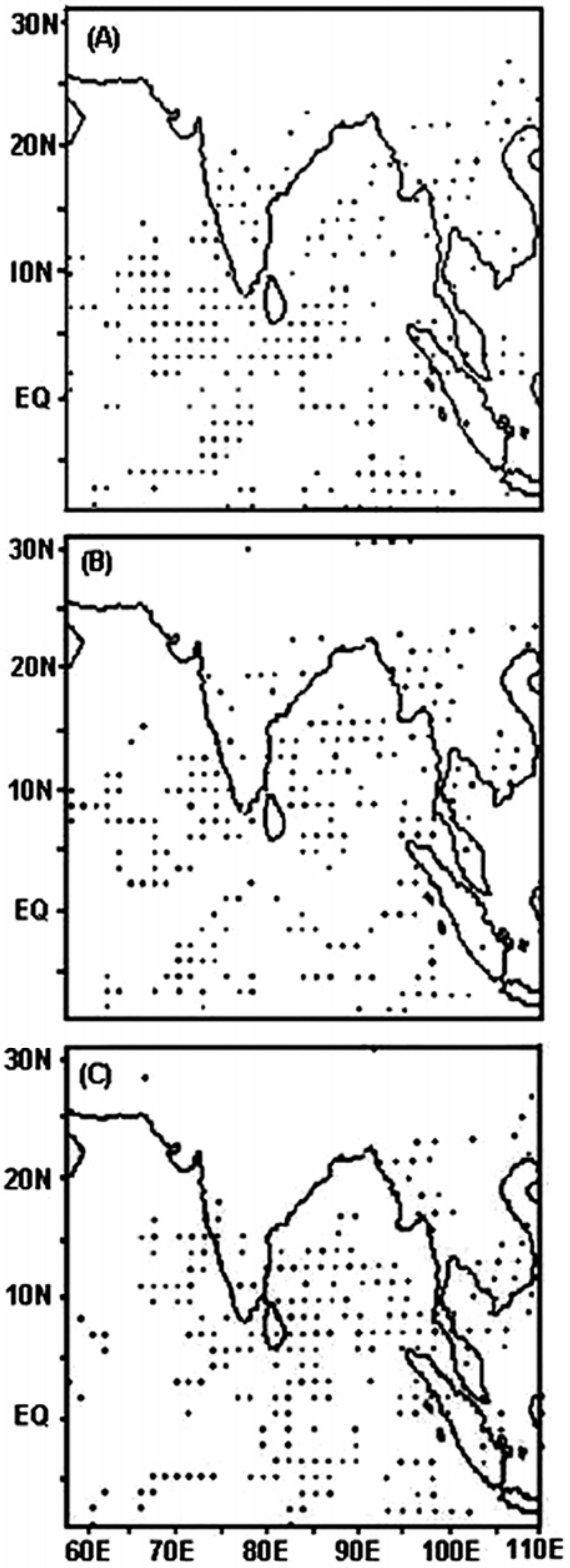

Fig. 6 — Coverage of METEOSAT-5 CMV data utilized in preparation of HRR for (A) 12:00 UTC 25 October, (B) 18:00 UTC 25 October, (C) 00:00 UTC 26 October 1999

high-resolution model grids could not reproduce the small-scale features already smoothed out in the large-scale reanalysis, in this experiment, the model is initialized with 12 hours analysis nudging before the start of actual forecast at 00:00 UTC 26 October 1999.

In the second experiment, the model initial condition is improved using satellite derived winds. For this purpose, high-resolution reanalyses are prepared for 12:00 UTC 25 October, 18:00 UTC 25 October and 00:00 UTC 26 October 1999 with coarse resolution NCEP/NCAR reanalyses as first guess and the satellite derived datasets described in section 4 as additional observations using Cressman's successive correction technique[27]. Finally, the model is initialized at 00:00 UTC 26 October using 12 hours nudging to high-resolution reanalysis. Simulation results from the first and second experiments will be referred as 'CONTROL' and 'SAT' simulations respectively.

Results and Discussion

(i) High-resolution reanalysis and model initial condition

The wind vector and magnitude at 1000 hPa in the HRR for 12:00 and 18:00 UTC 25 October and 00:00 UTC 26 October 1999 and corresponding NCEP reanalyses are presented in Fig. 7. The same at the model initial condition (00:00 UTC 26 October 1999) is also shown in Fig. 7 (D&H). The southwesterly wind converging to the storm is strengthened by 7 km/hr (44 km/hr in HRR compared to 37 km/hr in the NCEP reanalyses) in the reanalyses prepared with the insertion of satellite derived wind and also in the corresponding model initial condition. The stronger wind in the western sector of the storm in the HRR for 12:00 UTC 25 October (Fig. 7E) is mainly due to the wind vector from QSCAT. The impact is found to be little less in the reanalysis at 18:00 UTC 25 October (Fig. 7F). This is due to relatively less observations available for this period (no QSCAT data). Stronger southwesterly is mainly due to SSM/I ocean surface wind speed. Slightly stronger wind in the north-western part of the storm is due to observations from MSMR and METEOSAT-5. It is to be mentioned here that the direction of winds from SSM/I and MSMR is taken from large-scale first guess as these provide only the wind speed. The reanalysis valid at 00:00 UTC 26 October also shows stronger southwesterly in the southwest sector of the storm over the Bay of Bengal, which is mainly caused by SSM/I ocean surface wind. The initial condition also shows strong

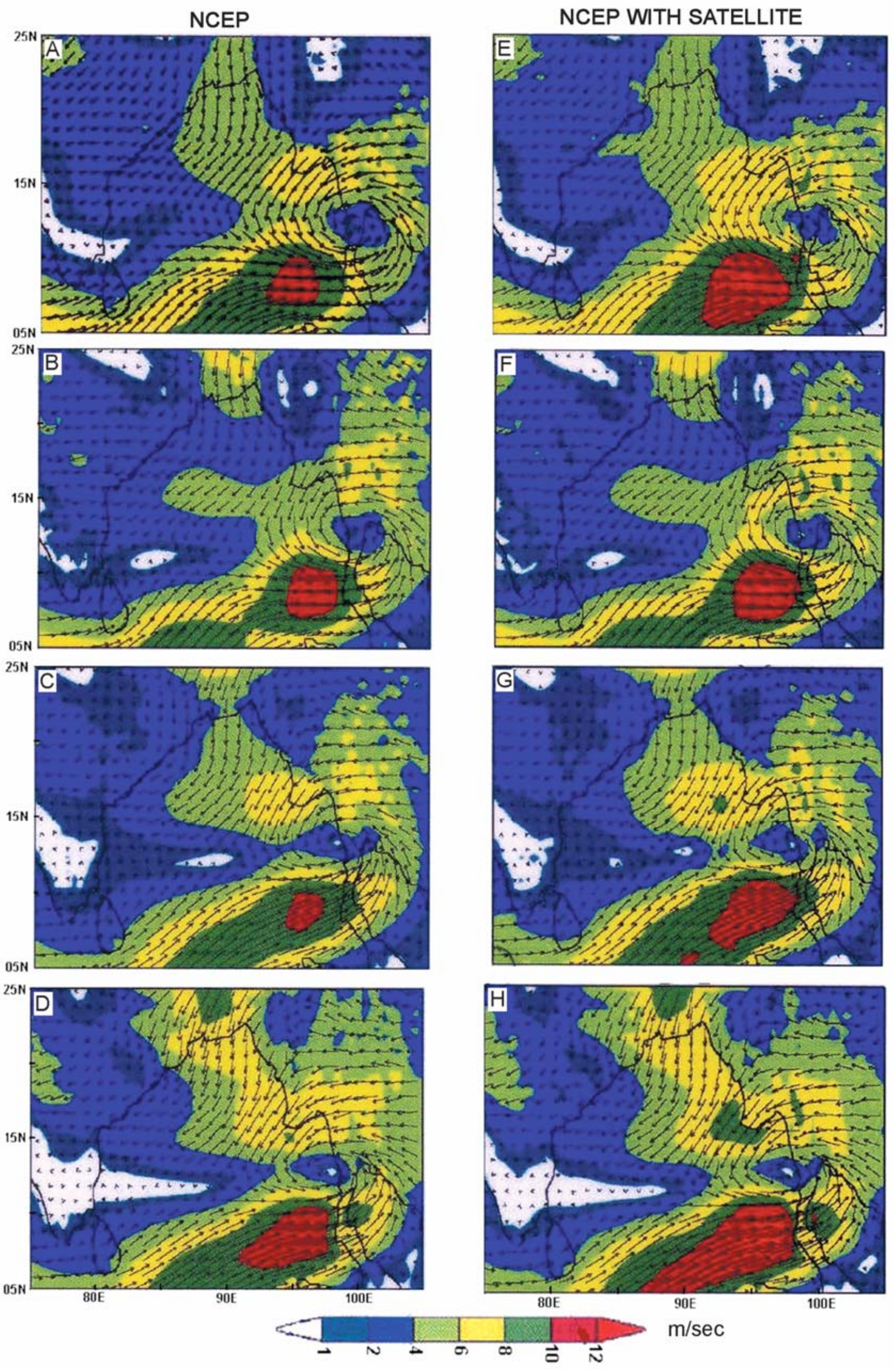

Fig. 7 — Wind at 1000 hPa in m/s (A)-(C) NCEP reanalysis valid at 12:00 UTC, 18:00 UTC 25 October and 00:00 UTC 26 October 1999 respectively, (D) valid at 00:00 UTC 26 after 12 hours analysis nudging, (E)-(G) same as (A)-(C) but improved with inclusion of satellite winds, (H) same as (D) but with improved analysis

southwesterly oceanic convergence to the vortex and is due to the combined effect of all available data. The flow pattern in 850 and 500 hPa (figures not shown) are not visibly modified with the incorporation of satellite datasets. Though, the easterly at 200 hPa is slightly strengthened with the inclusion of CMV from METEOSAT-5, it is not very significant. This is attributed mainly to less data coverage at these levels. Present study corroborates with the earlier study of Roy Bhowmik Sud[19] that reported positive impact (in intensity) of MSMR surface wind in the surface wind analysis during the development of tropical cyclone.

(ii) Impact on model simulations

The impact of satellite observations on model simulation is examined in this section through comparative discussion of the results obtained from the 'CONTROL' and 'SAT' simulations. All meteorological parameters have been examined in detail, but for the sake of brevity; the discussion is confined to mean sea level pressure, winds, rainfall and track of the storm.

a) Mean sea level pressure

The model simulated MSLP is presented in Fig. 8. During all 5 days, the large-scale pressure distribution patterns in 'CONTROL' and 'SAT' simulations are in close resemblance with the NCEP reanalyses. On day-1 and day-2 (figure not shown), the storm is more intense in 'SAT' simulation than that in 'CONTROL' simulation. On day-1, 'SAT' simulation shows central SLP of 997 hPa compared to 998 hPa in 'CONTROL' simulation and also in the observation. Similarly, on day-2, the storm was with central SLP of 983 hPa and 985 hPa respectively in 'SAT' and 'CONTROL' simulations. In addition, the storm is found to move slightly faster in the 'SAT' simulation (at an average speed of 19.4 km/hr in last 48 hours) compared to that in the 'CONTROL' simulation (at an average speed of 18.2 km/hr in last 48 hours). On day-3, though the intensity of the storm is same in both simulations (963 hPa), the location is better predicted by 73 km causing 37% improvement in 'SAT' simulation. The location of the storm is continued to be better in 'SAT' simulation on day-4 and day-5 as well. The storm continued to move faster in the 'SAT' simulation and is due to the better representation of the large-scale oceanic flow with insertion of satellite derived ocean surface wind. Relatively more intense storm on day-1 and day-2 in 'SAT' simulation is due to stronger initial vortex in the improved initial condition.

b) Wind at 1000 hPa

The model simulated wind magnitude and vector at 1000 hPa from 'SAT' and 'CONTROL' simulations is illustrated in Fig. 9. Though, there is no noticeable change in the flow pattern between the two simulations, the wind is marginally stronger in the 'SAT' simulation in day-1 and day-2. And the wind is found to be at its maximum strength in the southeastern sector of the storm. In 'SAT' simulation, the wind is stronger by 4 km/hr and 8 km/hr on day-1 and day-2 respectively compared to that in 'CONTROL' simulation. The most important aspect to note here is that in the 'CONTROL' simulation (day-5), the easterly flow in the northern and northeastern sector of the storm is stronger which might have caused the storm to move to the west on day-5. In 'SAT' simulation (day-5), there is strong southerly flow in the eastern and southeastern sector of the storm that caused almost northward movement of the storm in last 24 hours.

c) Precipitation

The 24 hours accumulated precipitation valid for day-3 to day-5 as obtained from 'CONTROL' and 'SAT' simulations are shown in Fig. 10. The precipitation on day-1 and day-2 is not validated as it was over ocean only. The subjective isohytal analysis over Orissa and adjoining areas is given in Fig. 11. Comparative study of these figures indicates that there is no significant change in the precipitation pattern in two simulations except on day-3. On day-3, the heavy precipitation band in 'SAT' simulation is found to be in the northeast of the precipitation band in the 'CONTROL' simulation. 'SAT' simulation shows relatively more precipitation (compared to 'CONTROL' simulation) over coastal Orissa that matches with the observation reasonably well. This is due to better positioning of the storm in 'SAT' simulation. Relatively smooth precipitation pattern in 'SAT' simulation is probably due to large-scale convergence from the ocean. The convergence of oceanic air mass is found to be stronger in the initial condition improved with satellite derived wind. It is to be noted here that no moisture field is introduced in preparation of high-resolution reanalyses and hence in the model initial condition.

d) Storm track

The track of the storm with the location in every 24 hours as obtained from 'CONTROL' and 'SAT'

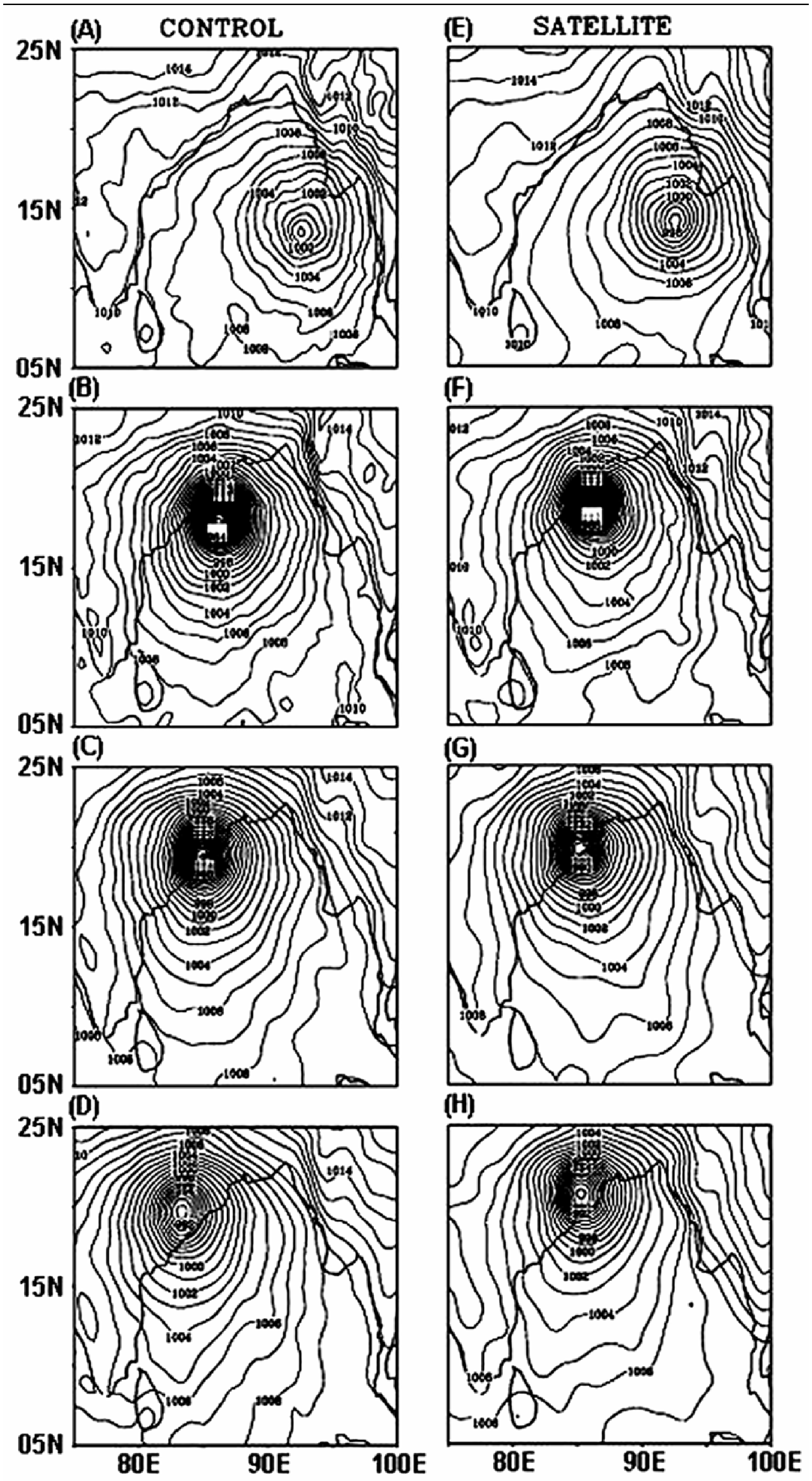

Fig. 8—Model simulated mean sea level pressure as obtained from ‘CONTROL’ and ‘SAT’ simulations valid at 00:00 UTC (A) 27 October, (B) 29 October, (C) 30 October, (D) 31 October 1999 from ‘CONTROL’ simulation, (E)-(H) same as (A)-(D) but from ‘SAT’ simulation

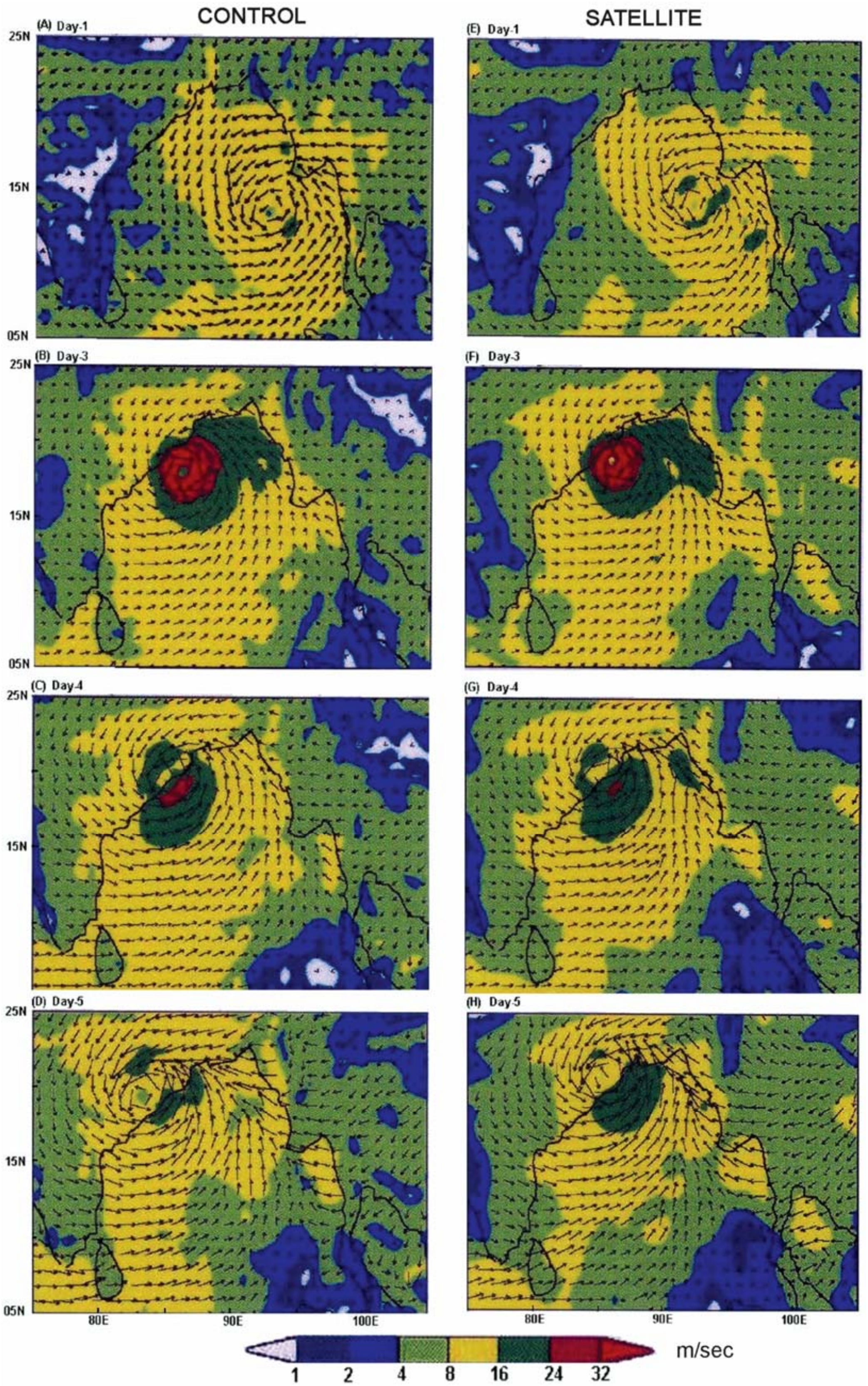

Fig. 9 — Wind magnitude and vector at 1000 hPa in m/s (A)-(D) valid at 00:00 UTC 27, 29, 30 and 31 October 1999 respectively from 'CONTROL' simulation, (E)-(H) same as (A)-(H) but from 'SAT' simulation

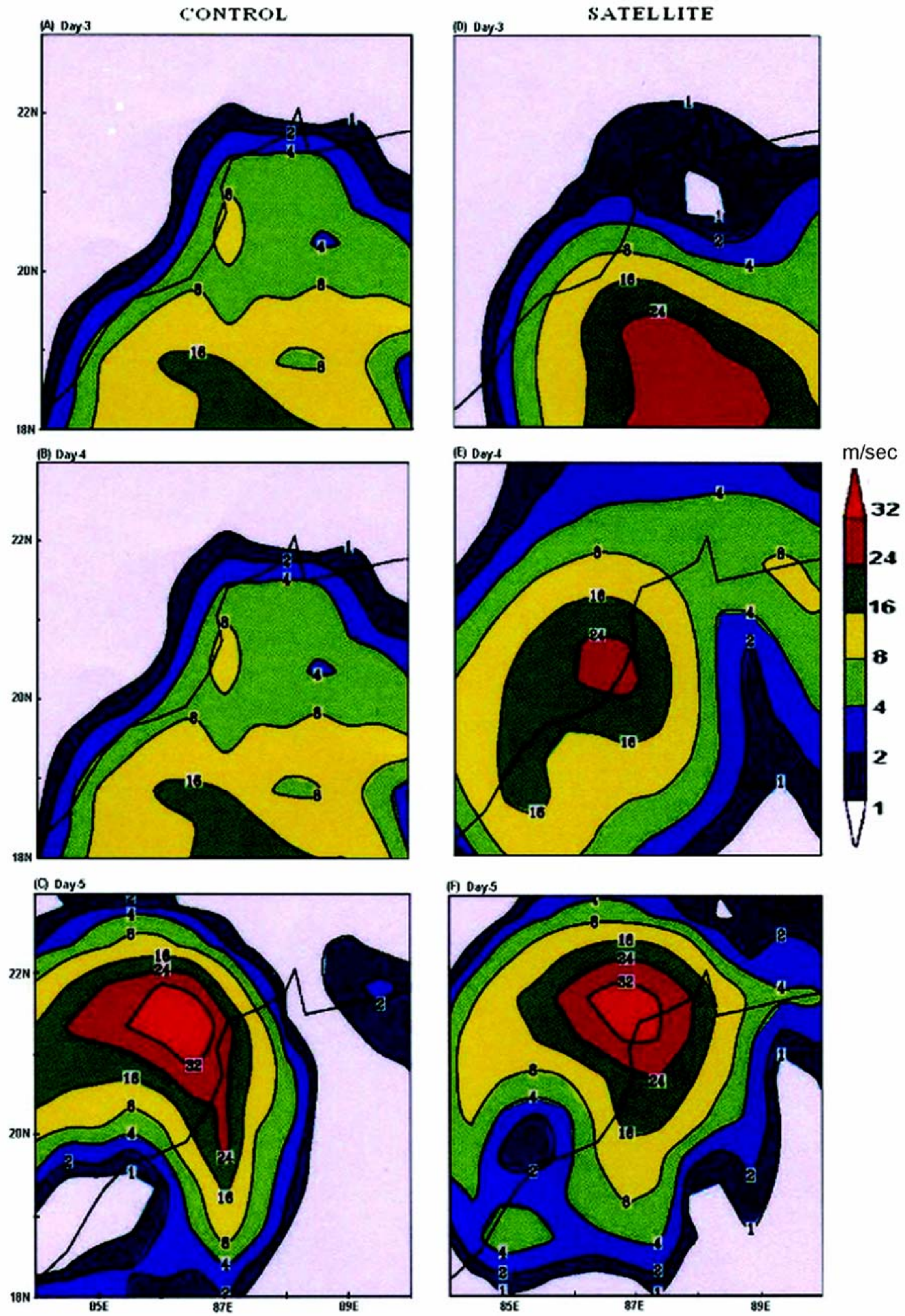

Fig. 10 — Model simulated 24 hours accumulated rainfall (in cm) valid at 03:00 UTC (A) 29 October, (B) 30 October, (C) 31 October 1999 from 'CONTROL' simulation, (D)-(F) same as (A)-(C) but from 'SAT' simulation

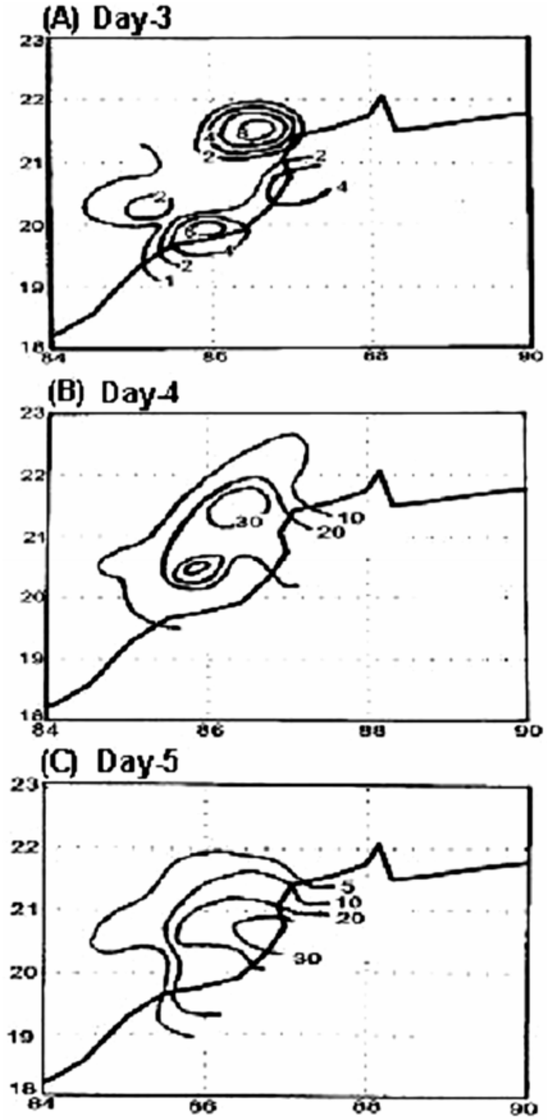

Fig. 11 — Observed 24 hours accumulated precipitation (in cm) valid at 03:00 UTC (A) 29 October 1999, (B) 30 October 1999, (C) 31 October 1999

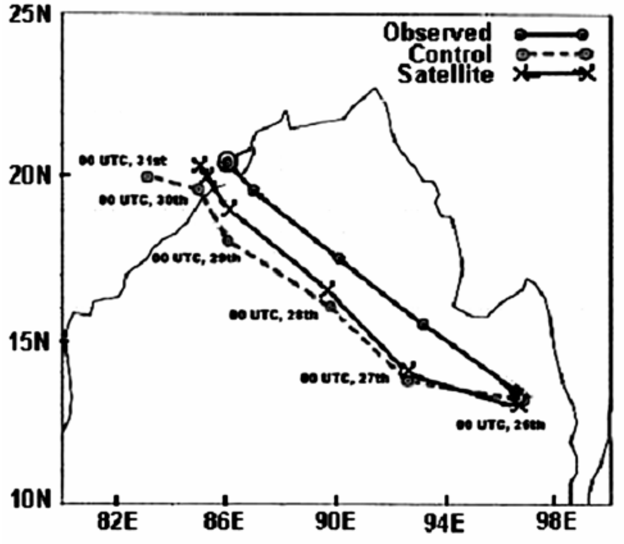

Fig. 12 — Track of the storm during 26-31 October 1999 as obtained from 'CONTROL' and 'SAT' simulations and also from observation (IMD best-fit)

Table 2 — Displacement errors in track forecast and percentage improvements in 'SAT' simulation w.r.t. 'CONTROL' simulation of Orissa super cyclone

Time	Displacement errors in km		% Improvement
	'CONTROL'	'SAT"	
Day-1	196	165	15
Day-2	157	104	34
Day-3	197	124	37
Day-4	137	99	29
Day-5	302	94	62

simulations along with the best (observed) track (from IMD) is provided in Fig. 12. As mentioned earlier, the storm is found to move faster in 'SAT' simulation in all 5 days providing consistently better track of the storm. Most importantly, the westward drifting of the storm in last 24 hours (as seen in 'CONTROL' simulation) is not found in 'SAT' simulation causing significant improvement in location of the storm. The vector displacement error in track forecast along with percentage improvement with the use of improved initial condition as compared to that in 'CONTROL' simulation is given in Table 2. This clearly indicates consistent and significant improvement in track forecast with inclusion of satellite-derived wind in model initial condition. There is an average 30% reduction in track error in first 4-day simulation of the super cyclone. On day-5, the error in track forecast is reduced by 62%. Soden *et al.*[28] indicated statistically significant improvement in predicting the track of hurricanes with the assimilation of satellite winds.

Conclusion

Satellite derived ocean surface wind from QSCAT, SSM/I and MSMR have visible impact in the high-resolution reanalyses and model initial condition prepared through 12 hours nudging to high-resolution reanalysis. The southwesterly wind (over ocean) converging to the storm and also the cyclonic vortex is strengthened with the incorporation of satellite winds.

Except in initial 48 hours, improvement in model initial condition with incorporation of satellite-derived wind does not show any noticeable change in the intensity of the storm (both in terms of pressure drop and strength of surface wind). But it caused faster movement of the storm resulting consistent and significant improvement in providing location of the storm. This in turn led to slight improvement in precipitation distribution and significant improvement in simulated track of the storm. The significant improvement in track forecast is in agreement with the findings of Goerss *et al.*[13] and Soden *et al.*[28], which indicated improvement in hurricane track forecast with the use of satellite derived wind.

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