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Role of Resolution on Atmospheric Dynamics during Fani Cyclone in the Indian Subcontinent

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ABSTRACT

A persistent discrepancy between mathematically modeled atmospheric circulation and observed precipitation has become increasingly evident over recent decades. High-resolution numerical weather prediction (NWP) models offer a pathway to reduce this gap, yet their practical deployment is constrained by limited data availability, high computational cost, and reliance on traditional model verification measures. This study proposes an efficient NWP framework implemented on small-scale parallel computing systems using an adaptive grid-resolution strategy within the well-known Nonhydrostatic Icosahedral Atmospheric Model (NICAM), enabling global weather analysis. By systematically varying horizontal grid spacing, the approach identifies the minimum resolution required to reliably capture mesoscale variations in wind, temperature, and precipitation while maintaining computational efficiency for targeted forecasting objectives. Global cloud-resolving simulations using NICAM are conducted under low-pressure conditions characteristic of cyclone formation over the Indian subcontinent, with specific focus on Cyclone Fani. Results show that even at reduced resolution, the model reproduces key atmospheric dynamics, including temperature, pressure, wind velocity, and precipitation at both near-surface and upper-atmospheric levels. These findings indicate that reasonable coarse-resolution NICAM simulations executed on small-scale parallel computing systems can effectively capture the essential atmospheric circulation associated with Cyclone Fani, providing a computationally efficient alternative for high-resolution numerical weather prediction.

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Keywords: Climate Model; Atmospheric Dynamics; Nonhydrostatic Icosahedral Atmospheric Model (NICAM)

1. Introduction

Weather forecasting has evolved significantly over the past century, transitioning from empirical and synoptic approaches to sophisticated numerical frameworks based on solving the governing partial differential equations of atmospheric motion^[1–4]. Today, modern forecasting is primarily driven by Atmospheric General Circulation Models (AGCMs), which incorporate complex representations of atmospheric dynamics, thermodynamics, radiation, and microphysical processes. The inclusion of advanced physical parameterizations and increasing spatial and temporal resolutions has substantially improved these models' predictive capability^[5–7]. In particular, high-resolution AGCMs are highly desirable due to their ability to explicitly resolve mesoscale and convective processes that are otherwise parameterized in coarse-resolution models^[8–12]. However, increasing model resolution comes at a high computational cost. The number of degrees of freedom grows rapidly with grid refinement, leading to substantial increases in computational time and memory requirements. Consequently, the deployment of such models requires the use of high-performance computing (HPC) systems. Although increasing spatial and temporal resolution can improve the simulation of extreme events, the associated computational cost limits its practical implementation, particularly in resource-constrained numerical modeling frameworks^[13–15]. Therefore, understanding the role of resolution is essential for achieving an optimal balance between accuracy and computational efficiency. Notice that the study of extreme events and their timely prediction over the Indian subcontinent region has been a focus for many researchers^[16–20].

Over the years, several high-resolution AGCMs have been developed, including the Nonhydrostatic Icosahedral Atmospheric Model (NICAM) which operates at sub-hundred-kilometer resolution. NICAM was developed by Tomita and Satoh and has been continuously improved through collaborative efforts^[21–23]. It employs a quasi-uniform icosahedral grid and a finite-volume discretization to solve the fully compressible nonhydrostatic equations of atmospheric motion. The model utilizes a horizontal explicit–vertical implicit

(HEVI) time integration scheme along with Runge–Kutta methods for temporal advancement, enabling stable and efficient simulations of atmospheric flows^[24].

A key advantage of NICAM lies in its use of the icosahedral grid, which avoids the singularities associated with traditional latitude–longitude grids and ensures a nearly uniform distribution of grid points over the sphere. This property enhances numerical stability and facilitates efficient parallelization, making NICAM well-suited for large-scale simulations on modern HPC architectures. The foundations of such grid systems can be traced back to earlier works on geodesic discretizations^[25], with further refinements improving grid quality and numerical accuracy. Additionally, advanced advection schemes developed for hexagonal–pentagonal meshes contribute to improved conservation and monotonicity properties^[26]. NICAM has demonstrated remarkable capability in simulating a wide range of atmospheric phenomena, particularly as a global cloud-resolving model. By explicitly resolving convective processes without relying on cumulus parameterization, NICAM provides a more physically consistent representation of cloud dynamics and precipitation systems^[27]. It has been successfully applied to study tropical disturbances, monsoon systems, and the lifecycle of tropical cyclones^[28–30]. High-resolution simulations have shown that NICAM can capture essential features such as convective organization, eyewall formation, and precipitation structures, which are critical for accurate cyclone prediction. Despite these advances, the use of ultra-high-resolution models remains constrained by computational limitations. This motivates the need for efficient strategies that balance accuracy and computational cost. One promising approach is to systematically investigate the impact of horizontal resolution on model performance and identify the minimum resolution required to capture key atmospheric processes. Such an approach is particularly relevant for regional phenomena like tropical cyclones over the Indian subcontinent, where accurate prediction of track, intensity, and precipitation is crucial.

In this study, we adopt an adaptive grid-resolution framework using NICAM to investigate atmospheric circulation under low-pressure conditions associated with cyclone formation. Global cloud-resolving simulations are conducted across

multiple horizontal resolutions, with a specific focus on Cyclone Fani. The objective is to assess how variations in grid spacing influence the representation of key atmospheric variables, including temperature, pressure, wind velocity, and precipitation across vertical levels. Furthermore, the simulations are designed to be computationally efficient, enabling their execution on small-scale parallel computing systems. The results demonstrate that even at relatively lower resolutions, NICAM is capable of capturing the essential dynamics of cyclone evolution, including large-scale circulation patterns and associated thermodynamic structures. This highlights the potential of combining efficient numerical frameworks with adaptive resolution strategies to reduce computational cost without significantly compromising physical accuracy. Such an approach is particularly valuable for operational forecasting and research applications in data-sparse and computationally constrained environments, especially in the context of cyclone prediction over the Indian region.

2. Mathematical Model of NICAM

The atmospheric motion is governed by the following system of fully compressible nonhydrostatic equations on an icosahedral horizontal mesh on a sphere:

$$\frac{\partial R}{\partial t} + \tilde{\nabla}_{h0} \cdot \frac{\mathbf{V}_h}{\gamma} + \frac{\partial}{\partial \xi} \left(\frac{\mathbf{V}_h}{\gamma} \cdot \mathbf{G}^z + \frac{W}{G^{\frac{1}{2}}} \right) = 0 \quad (1)$$

$$\frac{\partial \mathbf{V}_h}{\partial t} + \tilde{\nabla}_h \cdot \frac{P}{\gamma} + \frac{\partial}{\partial \xi} \left(\mathbf{G}^z \cdot \frac{P}{\gamma} \right) = -\tilde{\mathbf{A}}_h - \tilde{\mathbf{C}}_h \quad (2)$$

$$\alpha \frac{\partial W}{\partial t} + \gamma^2 \frac{\partial}{\partial \xi} \left(\frac{P}{G^{\frac{1}{2}} \gamma^{\frac{1}{2}}} \right) + Rg = \alpha \left(-\tilde{A}_Z - \tilde{C}_Z \right) \quad (3)$$

$$\begin{aligned} \frac{\partial E}{\partial t} + \tilde{\nabla}_{h0} \cdot \left(h \frac{\mathbf{V}_h}{\gamma} \right) + \frac{\partial}{\partial \xi} \left[h \left(\frac{\mathbf{V}_h}{\gamma} \cdot \mathbf{G}^z + \frac{W}{G^{\frac{1}{2}}} \right) \right] \\ - \left[\mathbf{V}_h \cdot \left(\tilde{\nabla}_{h0} \cdot \frac{P}{\gamma} + \frac{\partial}{\partial \xi} \left(\mathbf{G}^z \cdot \frac{P}{\gamma} \right) \right) \right] \\ + w \left(\gamma^2 \frac{\partial}{\partial \xi} \left(\frac{P}{G^{\frac{1}{2}} \gamma^{\frac{1}{2}}} \right) + Rg \right) \Big] \\ + Wg = \tilde{Q}_{\text{heat}} \end{aligned} \quad (4)$$

where,

$$\begin{aligned} \tilde{\mathbf{A}} &\equiv G^{\frac{1}{2}} \mathbf{A} \\ &= \tilde{\nabla}_{h0} \cdot \left(v_1 \frac{\mathbf{V}_h}{\gamma} \right) + \frac{\partial}{\partial \xi} \left[v_1 \left(\frac{\mathbf{V}_h}{\gamma} \cdot \mathbf{G}^z + \frac{W}{G^{\frac{1}{2}}} \right) \right] e_1 \\ &+ \tilde{\nabla}_{h0} \cdot \left(v_2 \frac{\mathbf{V}_h}{\gamma} \right) + \frac{\partial}{\partial \xi} \left[v_2 \left(\frac{\mathbf{V}_h}{\gamma} \cdot \mathbf{G}^z + \frac{W}{G^{\frac{1}{2}}} \right) \right] e_2 \\ &+ \tilde{\nabla}_{h0} \cdot \left(v_3 \frac{\mathbf{V}_h}{\gamma} \right) + \frac{\partial}{\partial \xi} \left[v_3 \left(\frac{\mathbf{V}_h}{\gamma} \cdot \mathbf{G}^z + \frac{W}{G^{\frac{1}{2}}} \right) \right] e_3 \end{aligned} \quad (5)$$

$$\tilde{\mathbf{C}} \equiv G^{\frac{1}{2}} \mathbf{C}, \quad (6)$$

$$\tilde{Q}_{\text{heat}} \equiv G^{\frac{1}{2}} Q_{\text{heat}}. \quad (7)$$

The variables in these equations are $R = \rho' G^{\frac{1}{2}} \gamma^2$, $P = p' G^{\frac{1}{2}} \gamma^2$, $E = \rho G^{\frac{1}{2}} \gamma^2 e$, $\mathbf{V}_h = \rho' G^{\frac{1}{2}} \gamma^2 \mathbf{v}_h$, and $W = \rho G^{\frac{1}{2}} \gamma^2 w$ where ρ , v , h , p , and T are the density, the velocity, the internal energy, the enthalpy, the pressure, and the temperature respectively. The subscript h denotes the horizontal components of operators or variables. Q_{heat} and g represent the heating rate and gravitational acceleration. Moreover, the variable t in the primitive equations is the notation for the time parameter. The parameters $e = C_v T$, $h = C_p T$, and $p = \rho R_d T$ are obtained by ideal gas assumptions, where R_d is the gas constant and C_v and C_p denote the specific heat at constant volume and pressure, respectively. NCEP data is used to generate the initial conditions, while the boundary conditions are prepared following the NICAM methodology^[27].

3. Numerical Discretization

3.1. Horizontal Resolution

In NICAM, the sphere is discretized by the icosahedral grid system. At the primary stage, such a system has 12 points over a sphere which are connected by triangular shapes, and this geometrical configuration consists of 10 diamond-like structures. This mesh grid system is named the *STD-grid*. The mesh resolution is represented by “g-levels-1,” where ‘l’ refers to the ‘l-th’ division of the grid. Next, further refinement is done by connecting the midpoints of the sides of a triangle, and this process is continued till the desired level of resolution is achieved^[26,31]. The horizontal grid resolution with respect to the different grid refinement levels is given in **Table 1**. Here, the geometry emerging by joining the gravitational centers of the adjacent triangles formed at a point is defined as a control volume. The geometric pattern of the control volume is hexagonal, except for its pentagonal shape at the twelve points of the g-level 0 icosahedron, as shown in **Figure 1**. For more details on numerical discretization, please refer to the literature^[24,26].

In this model, the computational mesh is based on an icosahedral grid system on a sphere. It provides quasi-uniform horizontal control volumes composed of hexagons and pentagons. Achieving a finer horizontal resolution significantly

increases the number of computational grid points, reaching the order of 10^7 degrees of freedom, see **Table 1**. Consequently, the NICAM has been developed for implementation on large-scale parallel computing systems using domain decomposition methods. The horizontal mesh is divided into multiple groups with an equal number of grid points. This ensures efficient load balancing among the MPI processes and improves computational efficiency and vectorization. For the g-level 9, we achieve the horizontal grid size ~ 14 km, which possesses 2,621,442 cells in a horizontal layer. Due to this region division method of NICAM, there is adopted a (i, j, k) dimensional array of computational data is adopted

to provide direct and continuous access to memory. Moreover, the i and j dimensions are also merged into a single dimension ij due to the large size of computational data in the innermost loops. Such sort of division makes the computational execution highly scalable for a large number of parallel processors using MPI with optimal efficiency. This is clearly evident from the strong scaling analysis data provided in **Table 2**. From **Table 2**, it is clear that for a fixed horizontal resolution (g-level 7 (≈ 56 km horizontal resolution), where the total degrees of freedom in the problem is 1,63,842, if we increase the number of processors, the execution time is reduced as expected.

Table 1. Geometrical parameters of the icosahedral grid for different g-level is the grid division level considering earth radius $R = 6,371.22$ km.

g-Level	Points	Arcs	Triangles	Average Interval (km)
0	12	30	20	7,142
1	42	120	80	3,571
2	162	480	320	1,786
3	642	1,920	1,280	892.8
4	2,562	7,680	5,120	446.4
5	10,242	30,720	20,480	223.2
6	40,962	122,880	81,920	111.6
7	163,842	491,520	327,680	55.80
8	655,362	1,966,080	1,310,720	27.899
9	2,621,442	7,864,320	5,242,880	13.949

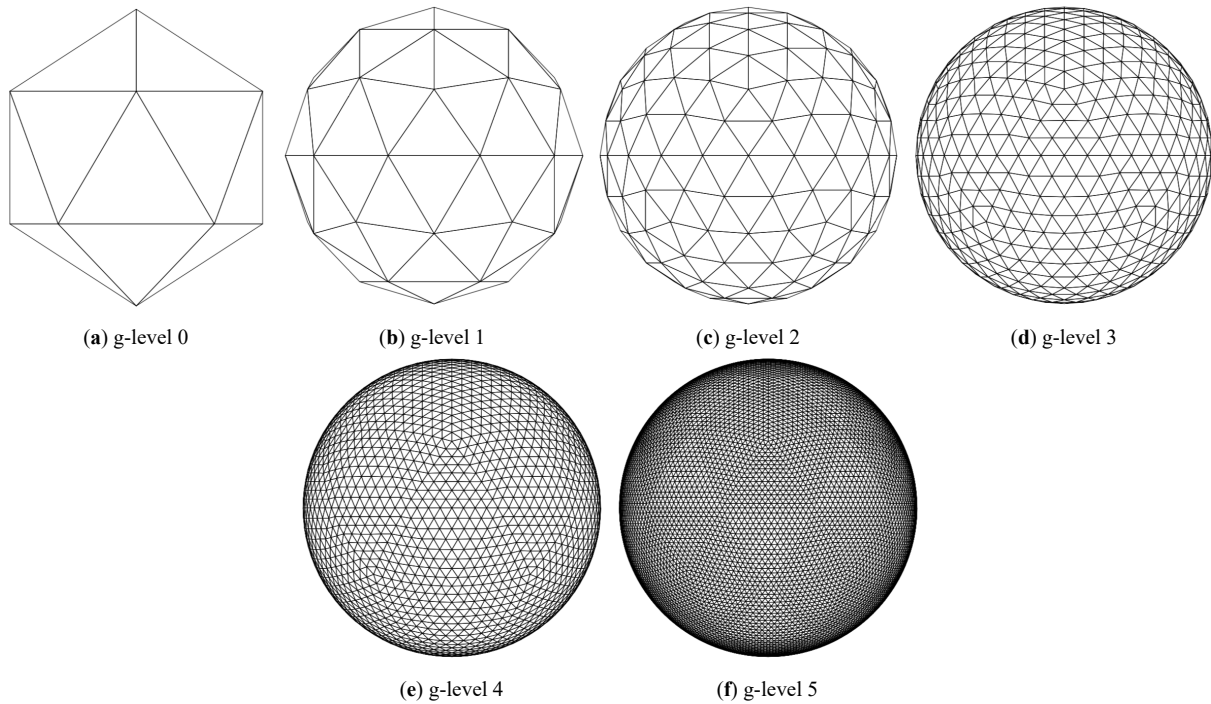


Figure 1. Schematic figure of the grid level discretization of the sphere w.r.to increasing g-levels.

Table 2. Performance against a fixed horizontal resolution.

g-Level	R-Level	Number of Processors	Time Taken (min:s)	Speed-Up (w.r.t 10 Processors)
7	2	10	36:20	
7	2	20	18:33	1.96
7	1	40	14:42	2.4
7	2	40	12:22	2.65

3.2. Vertical Resolution

In this model, vertical discretization is done using a terrain-following coordinate system with the Lorenz grid. Here, the horizontal velocity, density, and internal energy are evaluated at the full levels, and vertical velocity is computed at half levels. The geometric height is measured using the following mathematical relation:

$$h_{X,k} = H_k + \left(1 - \frac{H_k}{Z_{\text{top}}}\right) H_{X,\text{sfc}} \quad (1)$$

Here, H_k is the vertical level at index k . X , is horizontal location and Z_{top} , $H_{X,\text{sfc}}$ are top and surface heights respectively.

For the numerical solution of these equations, the finite volume method is implemented. For the time integration, a Runge–Kutta scheme with both the second- and third-order options is used. The acoustic wave conditions of Courant–Friedrichs–Lewy are taken care of using a split-explicit scheme along with a horizontal explicit and vertical implicit approach. It can be noted that the two types of numerical filters are used in NICAM for numerical stabilization. The first one is divergence damping which consists of the momentum equations with the addition of divergence damping terms to mitigate the instabilities associated with the time-splitting scheme. To neutralize the small-scale numerical disturbances, higher-order damping is used in NICAM instead of the widely implemented second-order divergence damping. The second is biharmonic horizontal diffusion, for which numerical terms are added to all the prognostic equations. Here, as the horizontal grid size is refined to half its size ($\Delta x \rightarrow \Delta x/2$) to increase the resolution by 2 factor, the diffusion time is halved to smooth the smaller-scale disturbances. Therefore, the large time step is kept ($\Delta t \rightarrow \Delta t/2$) when the g-level is increased ($n \rightarrow n+1$), and the default values for the non-dimensional coefficients corresponding to these numerical filters are set as $A_{dH} = K_H = 10^{16}$ for horizontal resolution 240 km (g-level-5) and $\Delta t = 1, 200$ s. In this century, computer systems possess higher power when

it is discussed in terms of computational ability, because of the presence of a large number of processors and memory modules. Even with the availability of such resources, we need to find the proper solutions to many features associated with the atmosphere. To attain high-precision numerical simulations by optimizing the computational cost, the future generation of atmospheric models should feature the customization of the number of grid points. For the testing of the impact of resolution on weather phenomena, we have analyzed the cyclonic events from the Indian Summer Monsoon 2019. For this, we have taken various horizontal resolutions of the global atmospheric model and prepared the boundary conditions for these. The initial conditions are prepared using linear interpolation from the observational data set by NCEP [32].

4. Results and Discussion

As we have discussed the mathematical modeling aspects of the resolution setup in terms of the magnitude of various parameters in the governing equations and parallel computation, the analysis of results in the present investigation can be illustrated by its two components. The first one includes analysis of weather through various pressure, temperature, and wind parameters and the comparison of NICAM simulation output on various horizontal grids with the observational data. The second part of the study includes the accuracy of the prediction of critical weather events. For this, we have taken cyclone Fani as a test case of the sudden development of unusual atmospheric conditions over the Indian region.

4.1. Environmental Conditions during the Cyclonic Formation of Fani

In this section, we discuss the physical phenomena associated with patterns of sudden formation of low-pressure zones in the Indian Ocean during the cyclonic formation

of Fani. The state of the atmosphere and its future prediction dependencies on the various factors associated with the resolution of the model are discussed here. For such a comparison, we have chosen three different resolutions as: (a) 223 km (g-level 5), (b) 56 km (g-level 7), (c) 14 km (g-level 9). To demonstrate the state of weather parameters and the dependence on atmospheric circulations, various parameters such as SST, pressure, and precipitation are analyzed. Here, the NICAM simulation's output for the 223 km (CR setup), 56 km (FR setup), and 14 km (HR setup) resolutions are plotted along with the observational result (NCEP data^[32]) and the related biases. For the analysis of atmospheric circulation during cyclone Fani, we have chosen the time interval for the numerical simulations to be April 27, 2019 to May 4, 2019.

The results in **Figure 2** depict the SST over the whole Earth surface for multiple resolutions on 27 April 2019 on the global scale. To get insight into the features of such visuals around the Indian region, we need to zoom in on these. Therefore, these results are taken over the region of rise and fall of the Fani cyclone and are depicted in the zoomed-in

region as shown in **Figure 3**. Moreover, the results portrayed in the following figures, and other figures in **Supplementary Materials** correspond to the sea surface temperature (SST), the sea level pressure (SLP), and precipitation, respectively, during this time interval. The results in these figures contain (a) NCEP observations, (b–d) NICAM output for 223 km, 56 km, and 14 km horizontal resolutions, respectively, and their relative biases under (e–g) for these horizontal resolutions, respectively. Here, from the SST visuals in **Figure 3**, we can see a better representation of the temperature profile at finer resolution. It can be noted here that increasing the precision of the terrain gradient at the land surface by increasing the resolution represents the topography in a better way. Moreover, a finer resolution leads to a significant enhancement of the orographic representation of the ocean region. It is evident from the SST visuals in **Figure 3** that lower temperatures ($\leq 300\text{K}$ (26.85°C)) over the southeast coastal region of India are captured well by the finer-resolution simulations of NICAM. Moreover, the warmer region in north India is better predicted by the 14 km resolution setup in comparison with others.

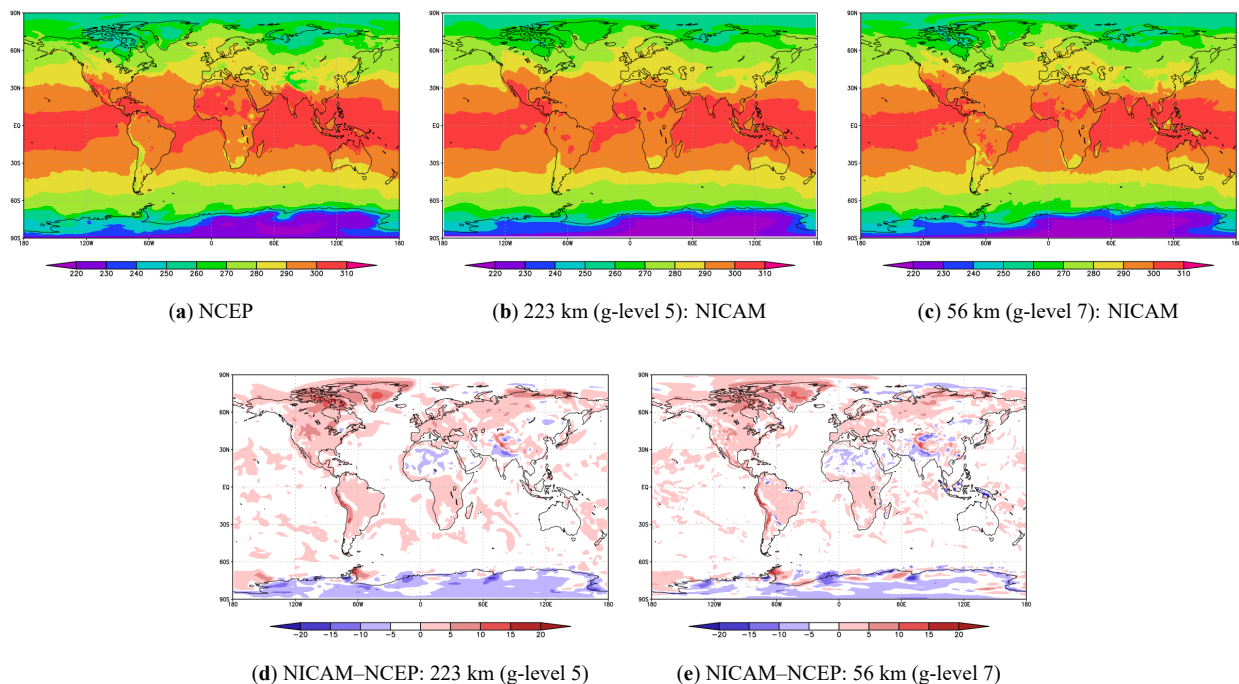


Figure 2. Global scale temperature (K) (2019:04:27:00).

From the results related to SST bias in **Figure 3e–g**, it is evident that the SST anomalies are within the acceptable range of $(-5, 5)$ everywhere, barring the northern India re-

gion around the Himalayas. Also, the mean relative error with respect to the minimum SST value is listed in **Table 3**. Statistically, the mean error in the temperature field varies

from 0.5 to 0.3 to 0.2 when the grid resolution is improved from 223 km to 56 km to 14 km, respectively. The variance in the error field increased from 4.0 to 6.6 to 10. It shows that the finer grid reduces the large-scale bias but introduces substantially more small-scale temperature fluctuations.

Moreover, it can also be observed that the SST anomalies with observational data decrease when resolution is increased. In the next three days till 30th of April, there is seen only a marginal change in SSTs is seen, but it diminishes the

SST Bias in the finer-resolution simulation output. On the 1st of May, the region of lower SSTs is elongated significantly in the output from the finer-resolution setup. On the next two days (2nd and 3rd of May), temperature fluctuations around the center of the Fani cyclone and the southern region of Sri Lanka are captured well by 14 and 56 km resolution configurations. On the other hand, post-cyclone SST predictions by higher-resolution results show greater anomalies in these regions.

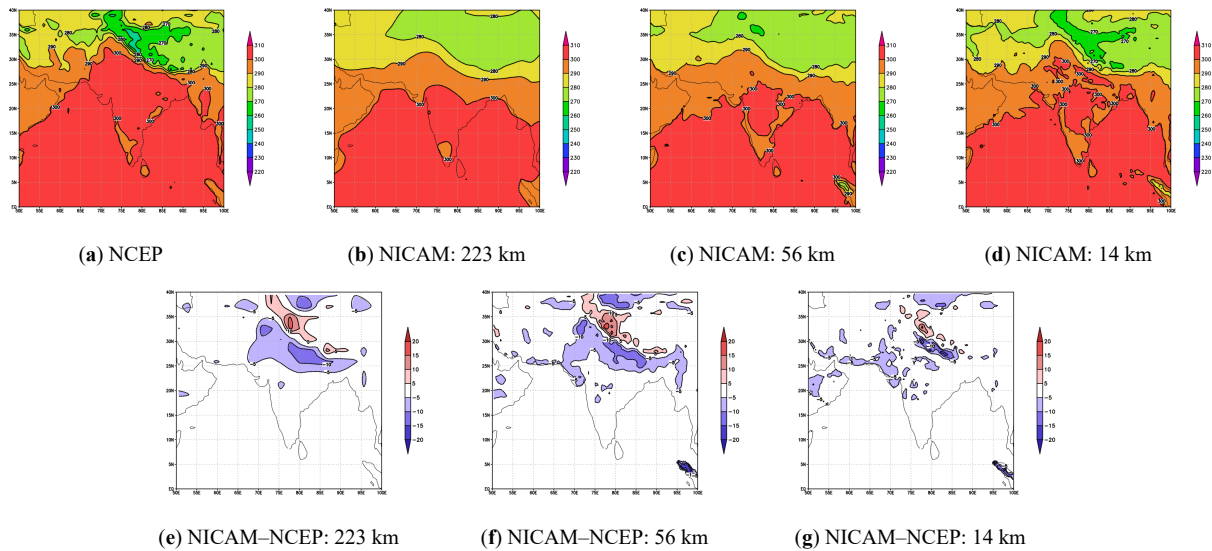


Figure 3. Temperature (K) (2019:04:27:00).

Table 3. Relative mean errors computed with respect to the minimum state-value.

g-Level	Relative Mean Error (SST)	Relative Mean Error (SLP)
5	0.22%	0.02%
7	0.13%	0.01%
9	0.09%	0.01%

From the **Figure 4**, it is seen that the sea level pressure on April 27, 2019 is between 1,000 hPa and 1,010 hPa over India and the ocean region around it. The mean relative error with respect to the minimum SLP value is listed in **Table 3**. Notice that the mean error in the pressure field varies from 0.2 to 0.1 to -0.1 when the grid resolution is improved from 223 km to 56 km to 14 km, respectively. The variance in the error field increased from 1.5 to 3.0 to 6.5. It shows that the finer grid reduces the large-scale bias but introduces substantially more small-scale pressure fluctuations. That is, the statistical trends for the temperature and the pressure field remain alike, and they produce more small-scale fluctuations with the increase in grid resolution. However, coarse

grids shows lesser small-scaled fluctuations, with the relative mean error remaining less than 0.5% for both the crucial variables SST and SLP. On the same day, the output from the 14 and 56 km resolution setups shows a small region having pressure below 1,000 hPa in the Bay of Bengal. As per the results of 28th of April (refer to **Supplementary Materials**), it transforms into a bigger region with pressure below 1,000 hPa. Such a growth in the low-pressure zone results in cyclonic development. This low-pressure zone expands with time and propagates towards the Indian coast till 2nd of May. Here, the results from the coarser resolution setup show a relatively larger low-pressure zone, which yields comparatively greater anomalies. Such results make evident

the fact that better prediction of atmospheric circulation is analogous to an increase in resolution. After 2nd of May, the low-pressure zone travels with the coastal region of India towards Bangladesh, which portrays the correlated cyclonic propagation of Fani. Here, it can also be noted that SLP anomalies from the results of the higher-resolution simulations are negative when the cyclonic atmospheric circulation is intensified over the ocean, and they become positive after

it strikes the coastal region.

Moreover, from **Figure 5**, the higher concentration of precipitation is seen in the Bay of Bengal area at (86° E– 88° E) to (6° N– 9° N) with the 56 km resolution setup. This region is larger in the case of 223 km resolution. Here, it can also be observed that the high-precipitation area travels with the low-pressure zone, and the higher-resolution numerical solution setup predicts it better.

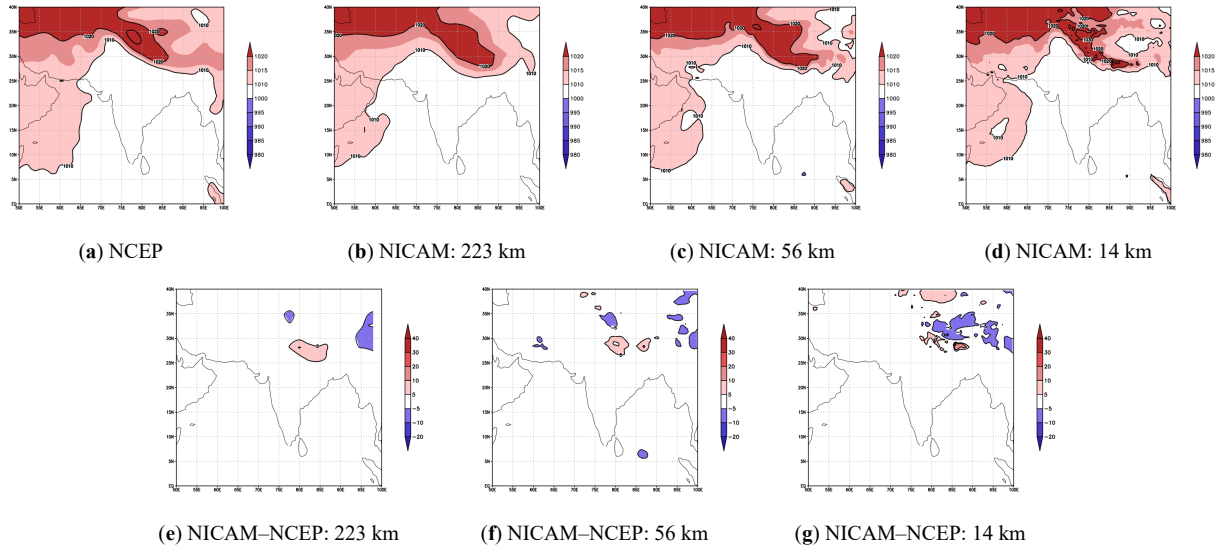


Figure 4. Sea Level Pressure (hPa) (2019:04:27:00).

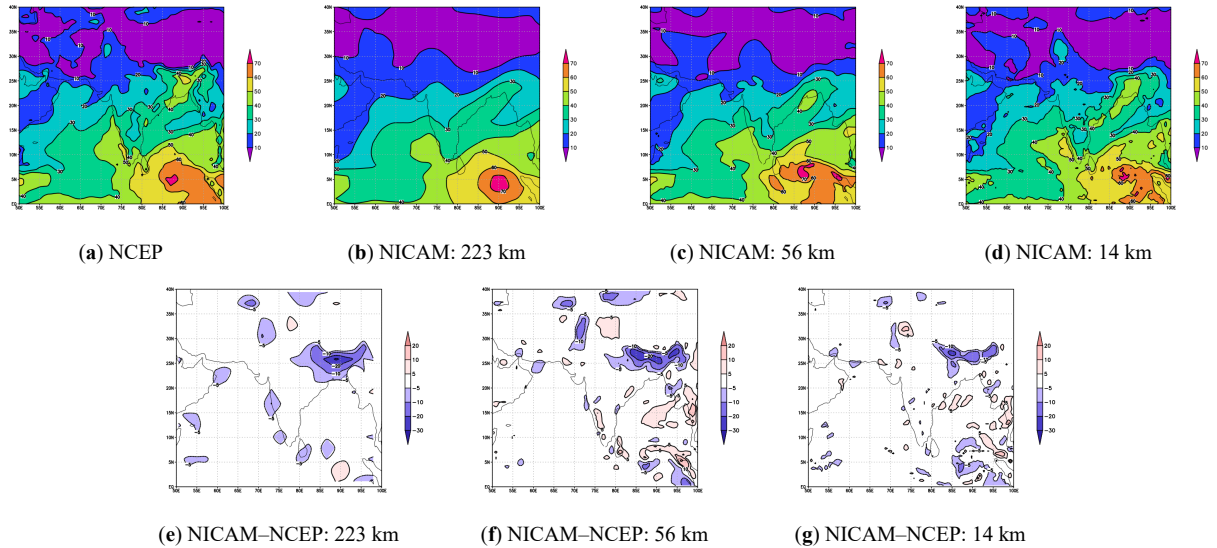


Figure 5. Precipitation (kg/m^2) (2019:04:27:00).

From **Figure 4**, there is seen a rapid intensification in the development of the cyclonic system in the specified short interval of time. The major contribution to such a process

is from the higher levels of sea surface temperatures and a further increase in these over the Bay of Bengal region. As per the simulated output, it can be clearly seen that there

is an abnormal rise in the SSTs over this region. In such a situation, ocean waters are found comparatively warmer even at greater depths (≈ 50 m). The higher temperature of ocean water ($T \geq 26$ °C) is the primary factor to trigger the low-pressure zone responsible for tropical cyclone-type formations. This effect is coupled with ocean thermal energy. Therefore, this process results in the production of energy through the evaporative-cooling effect, and its atmospheric circulation introduces the intensification of cyclone formation rapidly.

The upper atmospheric circulation at 500 hPa can be visualized by pressure in **Figure 6**, temperature and wind in **Figure 7**. The correlated atmospheric effects and their further propagation with time are observed from these figures, with lower magnitudes of pressure and temperature. As per

the results in **Figure 8**, it can be clearly seen that the spot tracing of the cyclone Fani center is efficient with the increase in the resolution. Moreover, when intensive cyclone-type atmospheric conditions are generated, there is noticed the higher sea-level-pressure anomalies are observed for greater horizontal resolution. The further intensification of cyclonic conditions leads to a greater increase in these anomalies (also refer to **Supplementary Materials**). Here, the positive amplitude of these anomalies shows the overestimation of these parameters when compared with the observations. On the other hand, the precipitation anomalies are found to be negative in amplitude over the cyclonic formation region, whether it is land surface or ocean. These precipitation anomalies are higher for coarser resolutions and get better in results of finer resolutions.

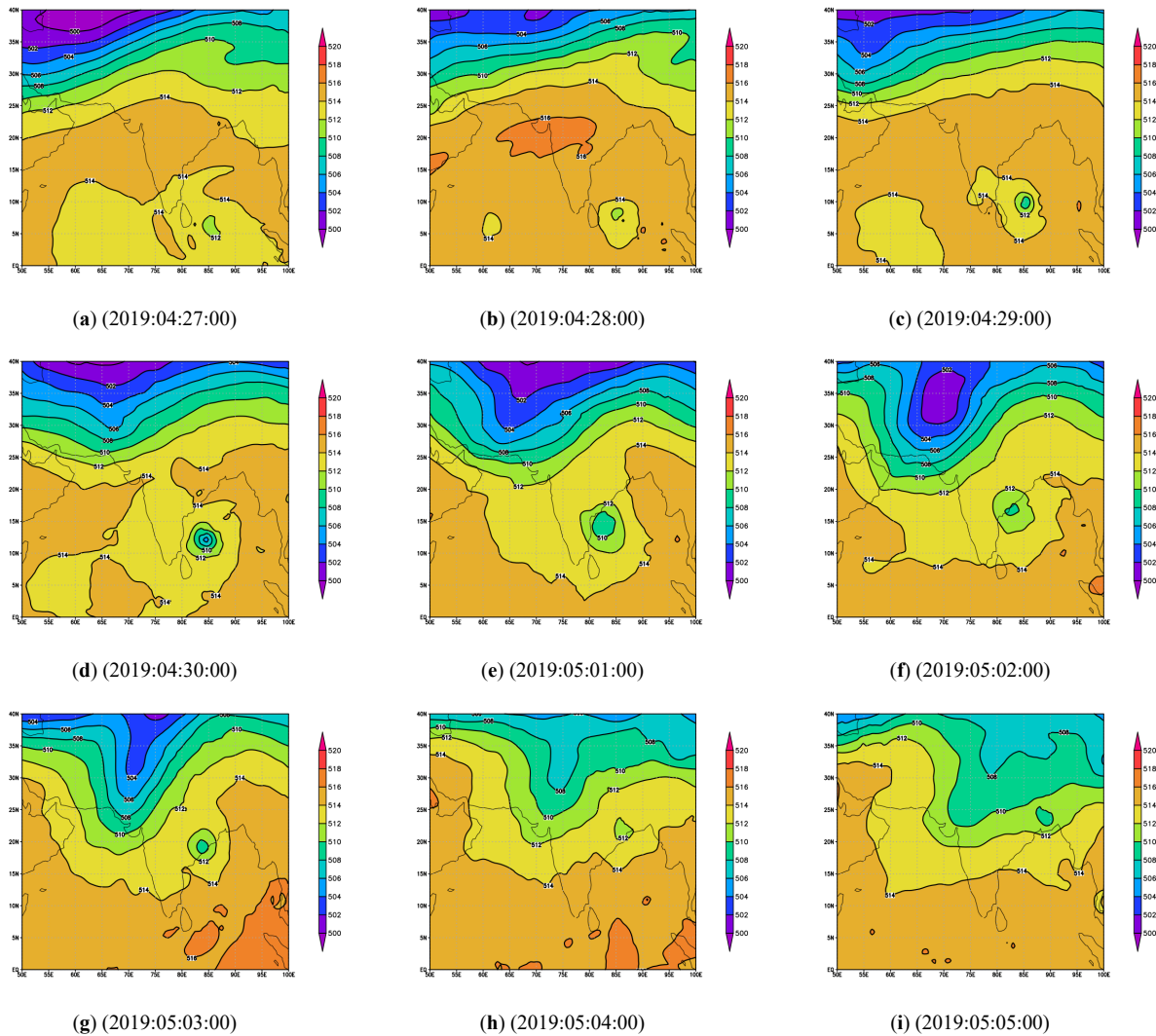


Figure 6. Pressure at 500 hPa.

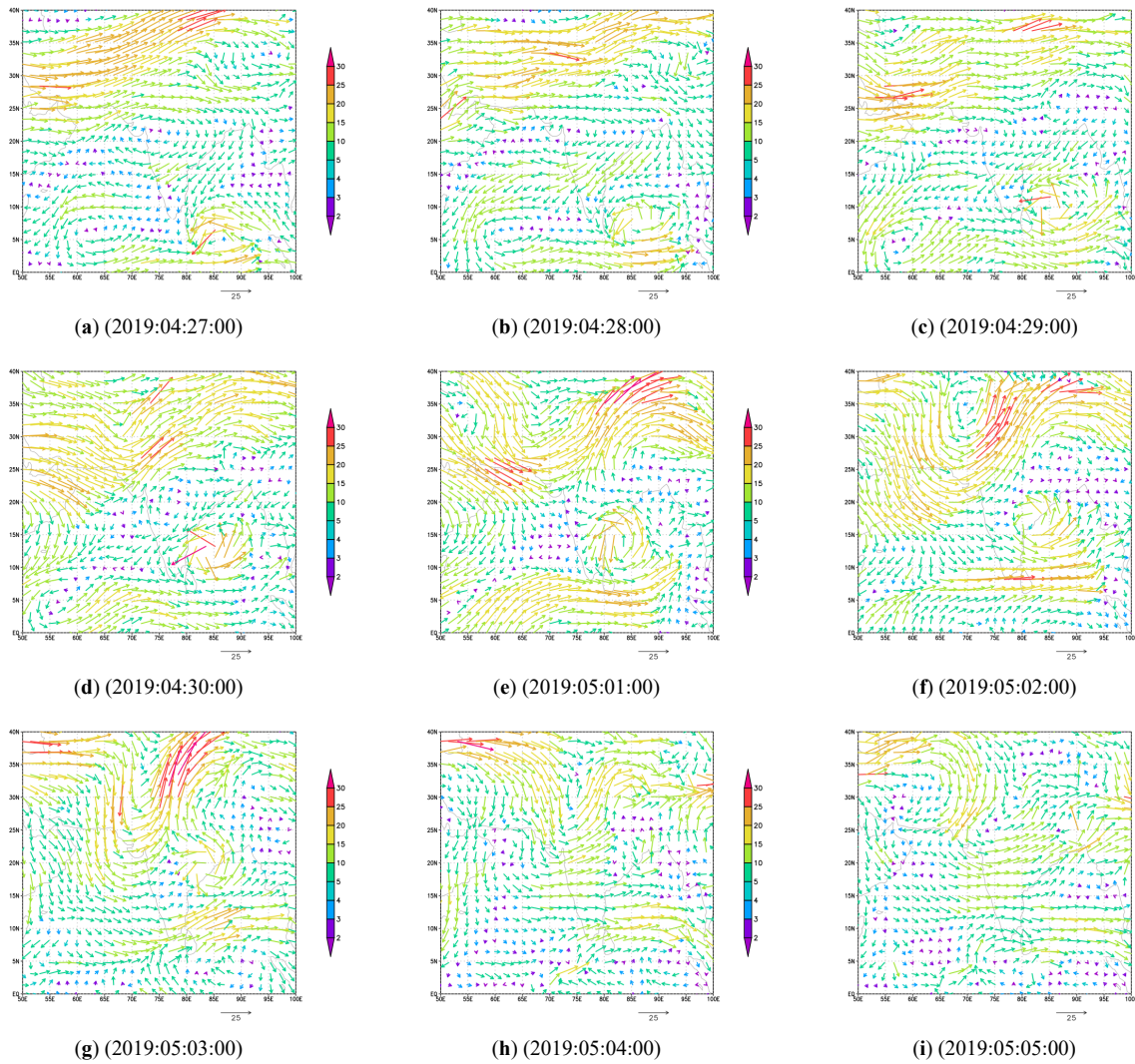


Figure 7. Wind at 500 hPa.

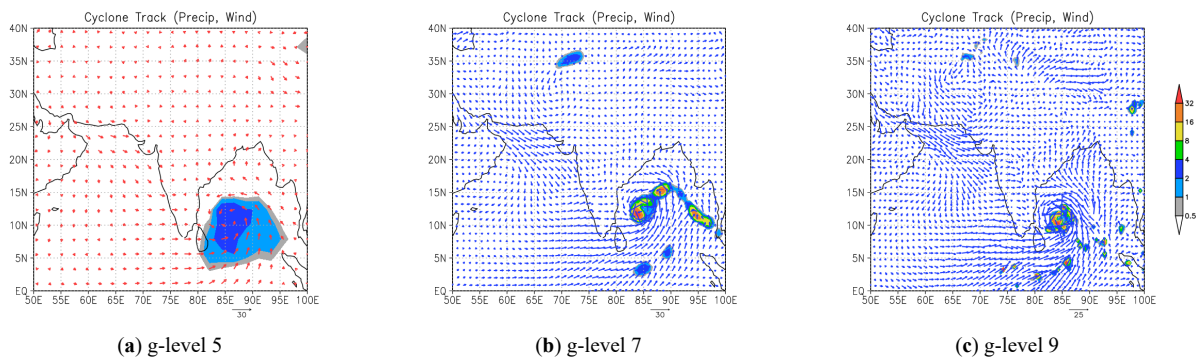


Figure 8. Cyclone Fani Comparison (2019:04:30:00).

4.2. Fani Track of Path

As per the results from NICAM, the cyclone named ‘Fani’ originated from a tropical depression that formed to

the west of Sumatra in the Indian Ocean on 25th of April 2019. On 26th of April, deep depression conditions formed, and these turned into a rapidly intensifying extremely severe cyclonic storm system.

The formation of a low-pressure center with high wind speeds (50–60 km/h) in the Indian Ocean leads to the development of strong winds, which result in heavy precipitation or rain. We can clearly see the anti-clockwise rotating precipitation patterns from the results. Further, a northward shift in the deep depression center is seen from **Figure 9a–c**, during 27–29 April, and it travels towards the Indian coastal region.

On 2nd of May, its peak intensity, is achieved possessing the high wind speeds (180–190 km/h) and extremely severe cyclonic storm formation. Just at the end of 1st of

May, its landfall can be observed from **Figure 9e** at the Odisha coast (16° N, 82° E). After its collision with the Indian coastal area, a significant weakening is observed in its intensity with its further northeast propagation on 3rd of May. Afterwards, the cyclone Fani loses its intensity and turns into a very severe cyclonic storm. On the next day (4th of May), Fani enters Bangladesh after the West Bengal region, and the cyclone's intensity is heavily diminished along with its further travel. In this period, a severe cyclonic storm profile is maintained with a wind speed in the range of 90–100 km/h.

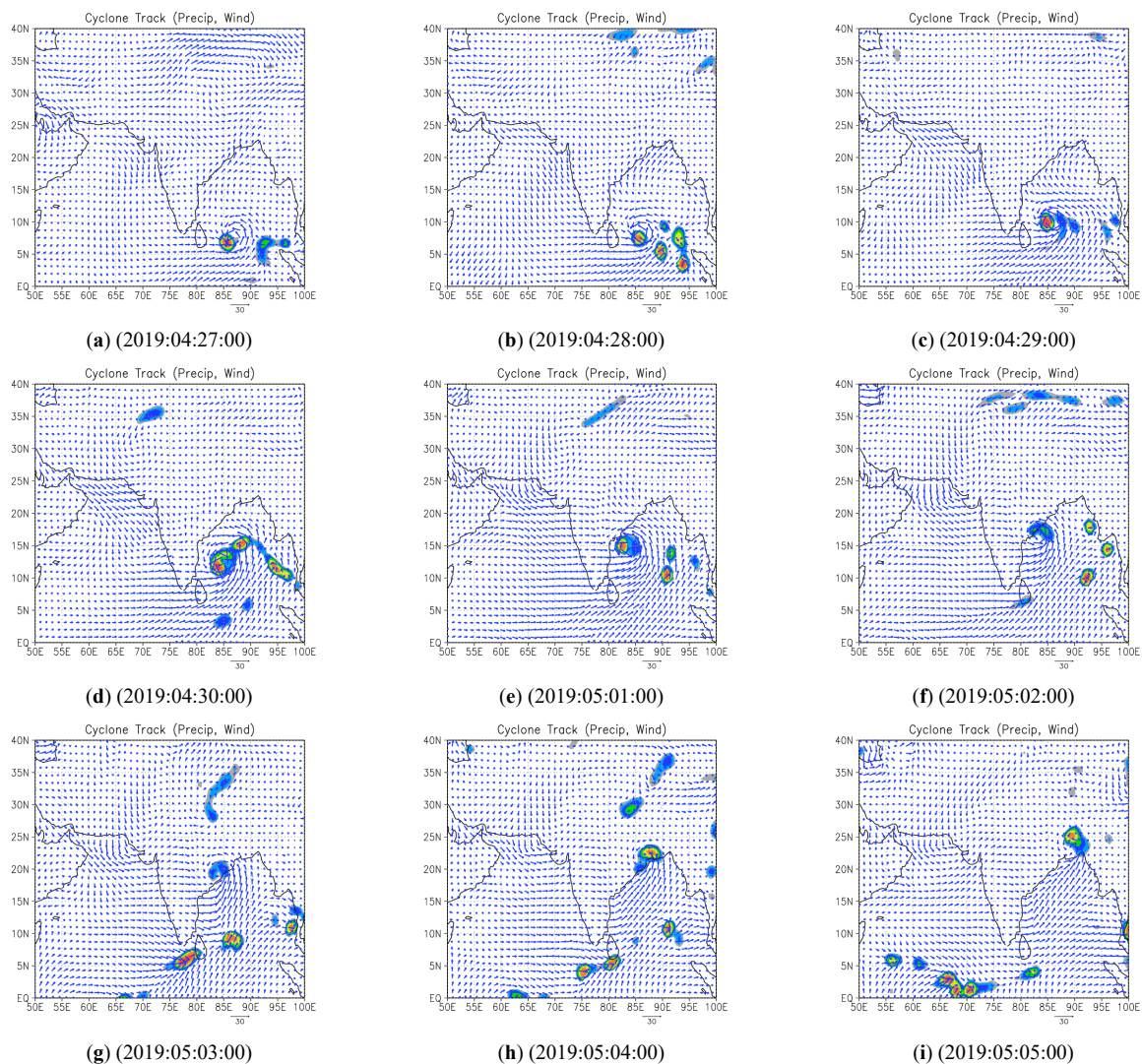


Figure 9. Cyclone Fani Track (56 km).

The diminishing surface-pressure levels with time, accompanying the intense swirling winds, describe the profile of the cyclonic event. These result in a decrease in the stability of moisture, leading to a drop in the shear. On 5th of May,

cyclone Fani enters the Assam region and loses its existence with deep depression conditions.

Here, the magnitude of the low pressure at the origin of cyclone Fani can be assessed by the comparison of the

MIN_{SLP} in **Figure 10** where MIN_{SLP} is the reported lower-level pressure intensity. Here, it is observed that the minimum value of SLP from the NICAM simulations is in good agreement with the observational data. It is also to be noted that SLP data from the NICAM simulations mostly show small positive biases with respect to the observational data. In essence, a comparison of the time evolution of cyclone Fani as reported by the NICAM simulations for g-level 5

is in good agreement with the reported observational data. Here, it can be noted that the cyclonic conditions are better portrayed by the g-level 7 (56 km) and g-level 9 (14 km) numerical solution setup. But the g-level 5 (223 km) has a reasonable capability to track the cyclonic development and its propagation, which is evidenced by good agreement of results corresponding to the MIN_{SLP} with the observational data as shown in **Figure 10**.

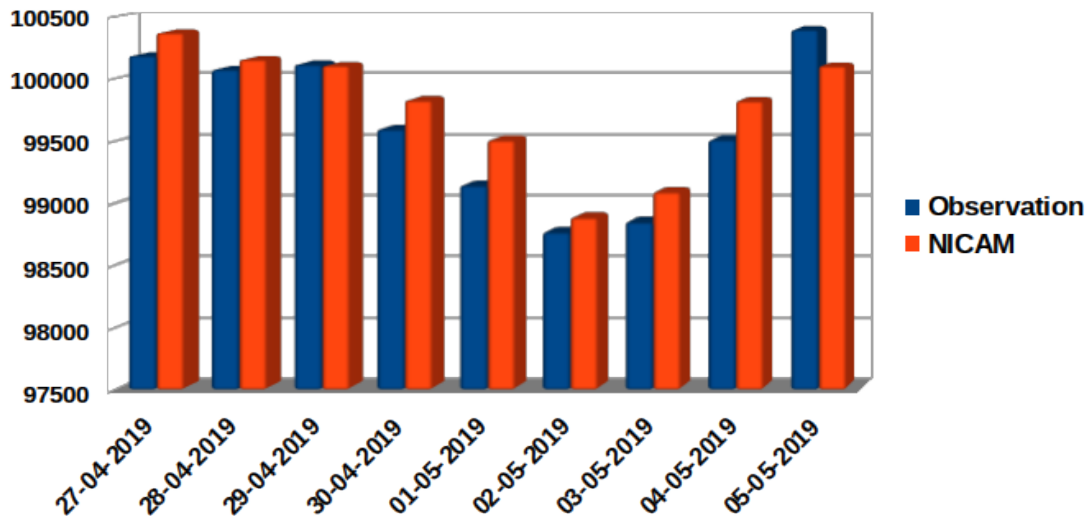


Figure 10. The diagram of minimum sea-level-pressure intensity during the cyclone Fani from the output of Observations (NCEP data^[32]) and NICAM simulations.

Additionally, it is also to be noted that both the g-level 5 and g-level 7 simulations have been successfully carried out on a small-scale parallel computing system at comparable CPU complexity with respect to the large-scale parallel computing system like Oakforest-PACS^[33]. This can be attributed to the compute nodes under SMP technology with dual Intel (R) Xeon(R) Gold 6,150 CPU 2.70 GHz, having 36 cores per board. Our small-scale computer is a rack of three such motherboards. Further, it may also be noted that we have used only 40 cores and 80 cores on the small-scale parallel computer for g-level 5 and g-level 7 simulations, respectively. The requirement on the Oakforest-PACS is also the use of a similar number of cores, though it has more than 500 thousand cores. For the g-level 9 simulations, one requires at least 2,560 cores. Here, we re-emphasize that the g-level 7 simulation outcome compares well, within the desirable accuracy on the global features, with the g-level 9 simulation outcome.

5. Conclusion

In view of the high cost in terms of computational resources for the correct projection of all-weather parameters from a high spatial and temporal resolution, the notion of adaptable horizontal cum vertical resolution, which has been validated against the observational data, can be a tactical tool for goal-specific numerical weather prediction with minimal time consumption. Therefore, we have investigated the various resolution schemes for the nonhydrostatic modeling based on the GFS NICAM to understand the state of the atmosphere during the evolution of suddenly developing weather events. The strongest pre-monsoon cyclone Fani, which developed after deep-depression conditions on the 25th of May 2019 in the Indian subcontinent region, is assessed for 223 km and 56 km horizontal resolutions on a small-scale parallel computer and for a 14 km horizontal resolution setup on the large-scale computer. The hindcast of the Fani cyclone using

the NICAM on these moderate resolutions is found to be successful and encouraging. Several gross quantities from the cyclonic analysis, such as SLP, SST, etc., are found to be in good agreement with the NCEP observational data. It is also to be noted that the prognostic variable results from the prior test are compared with the NCEP data, as a precursor to further study, and have been found to have a good correlation. Refining the grid from 223 km to 14 km reduces the mean temperature and pressure errors from 0.22% to 0.09% and 0.01% to 0.02%, respectively, while increasing their error variances from 4.0 to 10.0 and 1.5 to 6.5. Thus, while coarse grid accuracies are comparable to the fine grid accuracy, it is to be noted that finer grids depict more small-scale variability than coarser grids. Hence, for overall reasonable prediction of major prognostic features, coarse grids of the order 56 km, which can be handled on small-scale parallel computers, seem reasonable. The study shows that it is possible to arrive at a goal-specific adaptable horizontal resolution on a small-scale parallel computing machine. However, a complete analysis of very large-scale processes on a fine grid spacing is essential to predict all the subtleties of a cyclone with its intensity accurately.

Supplementary Materials

The supporting information can be downloaded at <https://journals.bilpubgroup.com/files/JASR-13484-Supplementary-Materials.pdf>.

Author Contributions

Conceptualization, B.V.R.K. and V.K.; methodology, B.V.R.K., V.K., C.P., S.P.B., S.K., and B.K.; formal analysis, B.V.R.K., V.K., and C.P.; resources, B.V.R.K. and B.K.; writing—original draft preparation, B.V.R.K., V.K., C.P., S.P.B., and S.K.; writing—review and editing, B.V.R.K., V.K., and C.P.; supervision, B.V.R.K. and B.K.; project administration, B.V.R.K.; software, V.K., C.P., S.P.B., and S.K.; validation, V.K. and C.P.; investigation, V.K., C.P., S.P.B., and S.K.; data curation, V.K., C.P., S.P.B., and S.K.; visualization, V.K.; funding acquisition, B.V.R.K. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement

Not applicable. This study does not involve human participants or animal subjects.

Informed Consent Statement

Not applicable.

Data Availability Statement

The datasets used in this study include NCEP reanalysis data and model-generated outputs from NICAM simulations. NCEP data are publicly available from the NOAA database. Simulation outputs can be made available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflicts of interest.

AI Use Statement

During the preparation of this manuscript, the authors used ChatGPT (OpenAI) solely for language refinement. No AI tools were used for data analysis, interpretation, or generation of scientific content. All outputs were critically reviewed and edited by the authors. The authors take full responsibility for the integrity and accuracy of the work.

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