Understanding the dependence of storm splitting on numerical models: Comparing UM and WRF

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Abstract
This article performs a systematic study to understand the dependence of the splitting of an initially axisymmetric storm on the various components of the Unified Model (UM) and Weather Research and Forecasting model (WRF). The models are adapted to keep their differences at a minimum. Results at km-scale grid resolution show that the models differ significantly even under a controlled environment with no surface and radiative forcing. The initial storm in UM splits into two within the first hour. WRF also produces two separate updraughts, but it does not split entirely because of a secondary downdraught that falls just ahead of the original updraught. The cold pool from this downdraught converges with the oncoming winds at lower levels to generate a ring of updraughts connecting the two. UM also shows a similar secondary downdraught, but it is relatively weak. Experiments with the successive reduction in complexity of the microphysics scheme show that the models start to differ with the inclusion of rain processes. Sensitivity experiments with the magnitude of turbulent mixing length do not impact this aspect of model behaviour. Resolution sensitivity experiments show that the storm does not split in UM for a horizontal resolution of \( O(100\text{ m}) \), whereas WRF behaves consistently across all the resolutions. Through further analyses, we argue that the formal accuracy of the model dynamical core has no control in deciding whether the initial storm will undergo a split or not.

Keywords
1. Tools and methods: numerical methods and NWP, 3. Physical phenomenon: clouds, convection, dynamics, microphysics, Unified Model, Weather Research and Forecasting model

1 INTRODUCTION

The life cycle of a thunderstorm is complex. While some thunderstorms remain isolated in their entire life span, some undergo a complex chain of interactions with their surroundings to result in weather systems that produce heavy rainfall for hours (e.g. squall lines). The consequence of one such interaction in a vertically
sheared environment is the splitting of a thunderstorm into two new thunderstorms that can stay even longer than the original storm itself (Klemp, 1987). Wilhelmson and Klemp (1978), Schlesinger (1975), and Thorpe and Miller (1978) were the pioneers to numerically simulate the splitting of an isolated thunderstorm in agreement with what was observed (Charba and Sasaki, 1971; Achtemeier, 1975). Wilhelmson and Klemp (1978) noted that splitting is a continuous process initiated by the precipitation-induced downdraughts, which split the original updraught at the centre of the storm. Thorpe and Miller (1978) also pointed to the role of downdraughts in storm splitting.

Later, Schlesinger (1980) revisited the problem to conclude that in addition to the downdraughts, the upward pressure gradient on the flanks of the original central updraught equally promotes splitting by allowing for an increased low-level convergence. He further analysed the contributions to the pressure gradient term from different sources to indicate that the primary source of this pressure gradient is the nonlinear advection term, which he termed as the dynamical pressure. Rotunno and Klemp (1982) investigated splitting under a directionally varying sheared environment and came to the same conclusion. Weisman and Klemp (1982), around the same time, studied the evolution of thunderstorms under different (unidirectional) environmental shear and surface buoyancy to highlight that splitting is preferred under a strongly sheared environment (about 0.01 s\(^{-1}\) over the first few kilometres). They further reported that the threshold buoyancy, indicated by surface humidity, required for an initial storm to sustain (and for it to split later) is \(\sim 12 \text{ g kg}^{-1}\) for weak shear (\(\sim 0.002 \text{ s}^{-1}\) over the first few kilometres) and that it increases with increasing shear. Gilmore et al. (2004) later extended the work by including ice microphysics, which was missing in the previous studies. However, the focus of their work was not on storm splitting.

While these studies provide a strong basis for understanding the reasons behind storm splitting under varying wind shear, it remains unclear whether this process is model-dependent or not. That is, can we assume that the initial storm in any model would split (not split) for a strong (weak) shear?

In a recent study, Zarzycki et al. (2019) compiled results from 10 new-generation dynamical cores in a similar set-up as Weisman and Klemp (1982). For the moderate shear employed (0.006 s\(^{-1}\) over the first 5 km), some of the models in their Figure 3 show the apparent splitting of the initial storm, whereas some of them do not. Two of the models (FV3: Lin, 2004; TEMPEST: Guerra and Ullrich, 2016) show an early sign of splitting of the initial storm, which appears to have merged towards the end of the simulation. NICAM (Tomita and Satoh, 2004) and CSU (Heikes et al., 2013) show two split storms with a few smaller storms in between them. ICON (Zängl et al., 2015) shows two split storms initially, but by the end of the simulation, the already split storms split further into two with an equally strong storm in the middle. MPAS (Skamarock et al., 2012) also shows two split storms but with an additional storm in the middle. The rest of the models show distinctly split storms.

The findings of Zarzycki et al. (2019) demonstrate that the early evolution of an initially axisymmetric thunderstorm is highly model dependent – even in an idealized framework. They further report that the models show convergence in the bulk quantities (e.g. domain-averaged rainfall) as the horizontal resolution is increased (from 4 km to 500 m), but the structural differences remain. Such differences in the numerical models are a matter of concern, especially in the light of growing interest in predicting high-impact weather (Clark et al., 2018). Without going into the details, Zarzycki et al. (2019) attributed those model differences to the model design parameters like the accuracy of the dynamical core, sources and magnitude of diffusion in the model, and dynamics–physics coupling.

The aim of the present work is to dive deeper into the problem. Here, we compare the Unified Model (UM: Brown et al., 2012) and Weather Research and Forecasting model (WRF: Skamarock et al., 2019) using the idealized set-up of Weisman and Klemp (1982). For the case considered, the initial storm in UM splits at a horizontal grid resolution of 1 km but not in WRF. We make a systematic investigation to understand this difference in model behaviour. How this difference and the model behaviour are affected by the cloud microphysical processes, turbulent mixing length, grid resolution, and model accuracy is discussed. Although the discussion here is focused on one particular aspect of storm evolution, the presented results highlight the processes that can cause significant differences in storm morphology in models even at km-scale resolution.

The motivation for the present work draws on our experience that the convective structures in WRF and UM are often very differently simulated. While WRF tends to keep them more organized, UM tends to have them broken (Jucker et al., 2020). We hope that the findings of the present work, although idealized, would provide some insight into such differences. The remainder of the article is organized as follows: Section 2 describes the two models and the experiment design. Results from various sensitivity experiments are presented in Section 3, followed by discussions in Section 4. The article is concluded in Section 5.
2 | EXPERIMENT DESIGN

2.1 | Model description

UM is a height-based non-hydrostatic model employing the semi-implicit semi-Lagrangian method to solve the equations (Wood et al., 2014). The semi-Lagrangian scheme in the UM offers a range of choices for spatial interpolation. In the present work, bi-cubic Lagrange in the horizontal and Hermite-cubic in the vertical are used for the temperature and moisture variables. Cubic-Lagrange is used for winds and density in all directions. All the physical processes are deactivated except for the cloud microphysics, turbulence, and the cloud scheme. The microphysics scheme is single-moment based on Wilson and Ballard (1999), and the turbulence scheme is three-dimensional (3D) Smagorinsky based on Lilly (1962). The Smith (1990) cloud scheme with critical relative humidity (RHc) parameter set to 1.0 is used for all the experiments. Further details of UM can be found in Brown et al. (2012).

WRF is a fully compressible non-hydrostatic model. Unlike UM, it uses a pressure-based vertical coordinate. It uses a third-order Runge-Kutta scheme for time integration and a fifth-order explicit upwind scheme for horizontal and vertical spatial discretization. A more detailed description of WRF can be found in Skamarock et al. (2019). Like UM, all physical processes are deactivated except for the microphysics and the turbulence scheme. WRF does not use a cloud scheme. The six-class single-moment WSM6 microphysics scheme (Hong and Lim, 2006) is used together with the 3D turbulence scheme based on Lilly (1962).

Standard model configurations, vn11.3 for UM and vn4.0.3 for WRF, are used. Attempts have been made to keep the physics in the two models as similar as possible to reduce the complexity when diagnosing model differences. However, some formulations are not modified as they provide a unique identity to the model because of their long-standing in the source code. These differences are described below:

- **Cloud scheme**: With RHc = 1, the Smith scheme allows for condensation as soon as saturation is reached at a given grid point, making it behave like a simple saturation-adjustment scheme as in WRF. This approach is commonly used in models designed for high-resolution simulations like UCLA-LES (Stevens et al., 2005) and ICON-LEM (Dipankar et al., 2015). There is a subtle difference in the way saturation-adjustment is performed in UM and WRF, which is worth nothing. In WRF, saturation-adjustment performed only once within the microphysics scheme called at the end of the time step, whereas in UM it is called twice—once before the call to the microphysics scheme at the beginning of the time step and again towards the end of the time step.

- **Stability functions in turbulence scheme**: The default implementations of the Smagorinsky turbulence scheme in UM and WRF are different. While UM uses the stability functions of Brown (1999) and applies a near-surface correction to the turbulence length-scale, WRF follows Lilly (1962) using \((1 - 3\lambda)1/2\) as the stability function (\(\lambda = \text{Richardson number}\)) without any near-surface correction. As the test case used in this article (detailed next) does not impose any surface fluxes and applies the free slip condition at the surface, the near-surface correction to the turbulence length-scale in UM has been removed. Stability functions in the models have been left untouched. However, we did perform a trial experiment by replacing UM stability functions with that of WRF and found that the findings reported here are not affected due to the difference in stability functions.

- **Mixing length in turbulence scheme**: The turbulent mixing length \(\lambda = c_s \Delta\) in both the models are different. UM uses \(\Delta = \max(\Delta x, \Delta y)\) and WRF uses \(\Delta = (\Delta x \Delta y \Delta z)^{1/3}\), where \(\Delta x\) and \(\Delta y\) are the horizontal resolutions, and \(\Delta z\) is the vertical resolution. We use the standard model formulations throughout the article. Experiments where the mixing length in UM was modified to be isotropic like WRF showed no difference in the model behaviour.

2.2 | Experiment set-up

The experiment set-up follows Klemp and Wilhelmson (1978) and Weisman and Klemp (1982) for a warm-bubble in an initially horizontally homogeneous atmosphere on a flat plane with no rotation. The bubble is axially symmetric of horizontal radius 10 km and vertical radius 1,400 m placed 1,450 m above the surface. The temperature perturbation added to the bubble is 2 K at the centre and decreases gradually to 0 K at the edge following cosine squared. The simulation domain is 500 km in the mean wind direction and 300 km across the mean wind direction with the doubly periodic condition at the lateral boundaries. There are no latent and sensible heat fluxes at the surface. The lower boundary uses a free slip condition for the horizontal velocities and no flux condition for the vertical velocity. Initial conditions are the same as that of Weisman and Klemp (1982), with the surface temperature at 300 K and the surface humidity at 14 g·kg⁻¹ (Figure 1). Low-level vertical shear (from 0 to 10 m·s⁻¹ in the first
2.5 km) is used in all the runs, as indicated in Figure 1. All simulations are integrated for 4 hours unless otherwise stated.

All experiments use the same vertical grid. The model top is at 38.5 km with 80 levels, standard in the operational runs at the Centre for Climate Research Singapore. Pressure values from one of the UM trial runs are used to create the vertical grid in WRF. This way, the vertical resolution and the level stretching in the models are nearly the same. The difference in their heights is less than 100 m in the troposphere and reaches a maximum of about 250 m towards the model top at $t = 0$ (Figure 2).

A set of experiments have been performed in this study to understand the roles of the cloud microphysical processes, turbulent mixing length, horizontal grid resolution, and model accuracy in splitting of the initial storm. CONTROL, which uses a horizontal resolution of 1 km and full cloud microphysics, is discussed in Section 3.1. NOICE is the same as the CONTROL but without ice processes (warm-rain microphysics only). Results from the NOICE experiment are discussed in Section 3.2. Results from the NORAIN experiment, which is the same as NOICE but without rain, are discussed in Section 3.3. Model sensitivity to turbulent mixing length and the grid resolution is presented in Sections 3.4 and 3.5, respectively, followed by a low-order WRF experiment in Section 3.6.

3 RESULTS

3.1 Experiment CONTROL

Figure 3 depicts the evolution of surface precipitation in the two models. The initial thunderstorm split into two by $t = 90$ min in UM, whereas it remains organized in WRF until $t = 240$ min. Integrating UM beyond $t = 240$ min (Figure 4) show precipitation patches forming next to the split storms (see the black circles in Figure 4), which causes the storms to reorganize. The storm in WRF, on the other hand, stays organized and continues to grow beyond $t = 240$ min (not shown).

Vertical velocity ($w$) contours at $z = 100$ m ($w100m$) in Figure 5 show the same behaviour but provide more insight into the storm's structure. Two updraught cores with a downdraught in the middle are visible as early as 30 min into UM simulation. The two cores are visibly connected at $t = 50$ min with the primary downdraught core
**FIGURE 3** Rainfall (shading in mm·hr⁻¹) for the UM (top) and WRF (bottom) CONTROL experiments, \( t = 30, 50, 90, 150 \) and 240 min [Colour figure can be viewed at wileyonlinelibrary.com]

**FIGURE 4** Rainfall (shading in mm·hr⁻¹) for the UM CONTROL after \( t = 240 \) min. The black circle at \( t = 270 \) min identifies the two updraughts that finally led to the reorganization [Colour figure can be viewed at wileyonlinelibrary.com]

(D1) behind and a new, relatively weak, secondary downdraught (D2) ahead of it. By \( t = 90 \) min, the two updraught cores split with the disappearance of D2. The rain contour that was over the D2 at \( t = 50 \) min also appears to be receding. The two updraughts continue to propagate until \( t = 150 \) min. An early sign of the reorganization of these updraughts is seen at \( t = 240 \) min. This reorganization is visible as a thin line of updraughts nearly perpendicular to the central axis (\( y = 150 \) km, referred to as Y150 henceforth) connecting the two split updraughts.
WRF shows similar features in the early phase of evolution. Two updraughts with a downdraught core behind them (D1) are seen at $t = 30$ min. At $t = 50$ min, it shows a sign of splitting with the primary downdraught (D1) behind the two updraught cores and a secondary, relatively stronger than in UM, downdraught core (D2) ahead of them. These two updraughts, however, never get fully separated. Instead, they produce a well-organized ring of the updraughts with downdraughts at the apparent centre of the ring by $t = 90$ min that continues to grow bigger in time to become a fully developed squall line by $t = 240$ min.

Early studies by Schlesinger (1980) and Rotunno and Klemp (1982) have indicated the role of the upward pressure gradient on flanks (across shear) of the original updraught in storm splitting. The understanding that emerges from the two studies is that the upward tilting of the low-level horizontal vorticity in an initially symmetric thunderstorm creates low pressure on the updraught flanks at the mid-levels. The low pressure leads to an anomalous vertical pressure gradient on the flanks attracting the winds at the lower levels, making the original updraught devoid of the winds. This vertical pressure gradient forms the seed for the storm’s subsequent splitting, which accelerates due to the falling rain.

To see if the storm in UM splits due to the same reason, Figure 6 shows the across-shear ($z$-$y$) vertical cross-section of the pressure anomaly in UM and WRF. The cross-section passes through the maximum vertical velocity points at $z = 1.5$ km, as indicated by the black lines in Figure 5. The anomaly is with respect to the initial condition. Velocity vectors (black arrows) and a cloud contour (liquid water + frozen species $= 0.2$ g·kg$^{-1}$, in purple) are overlaid in the figure to aid understanding. At $t = 50$ min, both the models show low pressure on the flanks of the initial updraught centred at $z = 3$ and 4 km in UM and WRF, respectively. It also shows the inflow of winds at the lower levels. Forty minutes later ($t = 90$ min), those low-pressure regions in UM have moved further apart, causing the storm to split. Those low-pressure regions have also moved apart in WRF but not as much. It suggests that both the models possess an initial tendency to split and have two separate updraughts on the flanks of the initial updraught. These two updraughts ultimately split in UM but not in WRF. In the following, we will try to understand why the storm does not split in WRF.

A close inspection of $w100m$ (Figure 7) in WRF shows that the two updraughts, which appear connected through a line of updraughts at $t = 50$ min, are disconnected 10 min later. This disconnection implies splitting of the initial updraught at the lower levels. At the same time, however, a ring of updraughts is also seen forming ahead of D2. By $t = 70$ min, the downdraughts D1 and D2 have merged, and the resulting cold pool from them converges with the oncoming ambient wind to provide the necessary moisture flux for the survival of the updraught-ring.
The secondary downdraught D2 appears to be the key in the formation and survival of the updraught-ring in WRF. To see how D2 is formed, we plot the along-shear \((z-x)\) vertical cross-section of vertical fluxes of all the frozen hydrometeors (ice, snow and graupel; top) and rain (bottom) in Figure 8. It is noted that the outgoing winds from the updraught (Figure 8a) turn downward at \(z > 6\) km, contributing to the downward flux of the hydrometeors. While the winds at \(z > 6\) km have both downward and eastward components of the velocities, they are mainly downward at \(z < 6\) km, as can be seen near the green arrow in Figure 8a. These precipitating hydrometeors are the primary source of the downward flux of rain in Figure 8c, which then forms D2 as indicated in the figure. The subsequent merging of D1 and D2 and the formation of an updraught ahead of them are seen in Figure 8d. Unlike in Figure 8a, the downward flux of the hydrometeors in Figure 8b is found to originate predominantly at \(z = 6\) km (see green arrow) with no contribution from the winds going out of the updraught. The source of this downward wind component at \(z = 6\) km is discussed next.

The horizontal cross-section of the WRF pressure anomaly at \(z = 6\) km (Figure 9c,d) shows two blobs of low pressure at \(t = 50\) min. These blobs correspond to the low-pressure region on the flanks of the initial updraught shown in Figure 6d. The horizontal winds turn around these blobs and converge with the eastward winds just behind them (see the black circle in Figure 9c). The winds turn similarly in Figure 9d and converge with the eastward wind, but this time they also converge with each other ahead of the blobs at \(x \approx 202\) km. This convergence zone coincides with the location where the flux in Figure 8b (the green arrow) starts to be dominantly downward. It appears that the ambient winds drawn towards
**FIGURE 7** Vertical velocity (shaded, m·s$^{-1}$) and rain (green contours of 0.05 and 0.2 g·kg$^{-1}$) at $z = 100$ m for the WRF CONTROL experiment. Vectors are the storm-relative (a mean storm speed $u_s = 8$ m·s$^{-1}$ is subtracted from the $u$-wind) horizontal wind. D1 and D2 indicate the primary and secondary downdraughts, respectively [Colour figure can be viewed at wileyonlinelibrary.com]

**FIGURE 8** Vertical cross-section ($z$-$x$) along the centre of the $y$-axis (Y150) showing the contours of mean vertical fluxes of the (a,b) frozen hydrometeors and (c,d) rain, from the WRF CONTROL. Mean is calculated over five points on both sides of Y150. Storm-relative plane-parallel wind vectors (a mean storm speed $u_s = 8$ m·s$^{-1}$ is subtracted from the $u$-wind) are shown. The primary and the secondary downdraughts (D1 and D2) identified in Figure 7 are marked in (c). The green arrows in the top panels indicate the height where the winds turn mainly downward. The black arrow in (d) marks the new updraught [Colour figure can be viewed at wileyonlinelibrary.com]
these low-pressure blobs bring with them hydrometeors from the two updraughts, which lose their buoyancy after mixing with the ambient air and start to fall upon the convergence. These falling hydrometeors contribute to the total downward flux of the hydrometeors in Figure 8b. Although not shown, the same phenomenon takes place also at $z = 4\,\text{km}$, suggesting that it is primarily a mid-level phenomenon.

The UM (Figure 9a,b) also shows winds turning around the low-pressure blobs and converging with the eastward wind just behind them at $t = 50$ and 60 min. However, differences are that the anomaly in these blobs is not that strong and that the convergence ahead of them is weak, the result of which is that there are less precipitating hydrometeors in UM (Figure 10a,b), which in turn has resulted in a weaker D2 (Figure 10c) that soon merges with D1 (Figure 10d) and disappears (also see Figure 5, $t = 90$ min).

From the discussion so far, it is clear that the initial storm splits into two in WRF also, but only at the lower levels. The secondary downdraught that forms ahead of the updraughts at around $t = 50$ min helps generate a ring of updraughts that connects the two separate updraughts. All this happens within 10–20 min, as shown in Figure 7. The split storms in UM also reorganize but after a few hours. Furthermore, the way the split updraughts eventually connect in UM is not the same as in WRF. Figure 11 shows the sequence of $w_{100\text{m}}$, leading to the formation of

FIGURE 9  The horizontal section at $z = 6\,\text{km}$ showing pressure anomaly (shaded, Pa) with cloud (purple contours) for CONTROL. Vectors are the storm-relative (a mean storm speed $u_s = 8\,\text{m}\,\text{s}^{-1}$ is subtracted from the $u$-wind) horizontal wind. The black circles mark the regions of wind convergence. (a,b) UM and (c,d) WRF [Colour figure can be viewed at wileyonlinelibrary.com]
the updraught-ring in UM. At $t = 240$ min, the westward winds converge with the cold pools at the leading edge (see the arrows) of the updraughts. Soon, at $t = 270$ min, the cold pools on either side of Y150 come sufficiently close to converge with the oncoming winds almost perpendicular to Y150. This wind convergence across Y150 causes the updraughts to ultimately connect at $t = 300$ min to form an updraught-ring later.

### 3.2 Experiment NOICE

Although UM and WRF use similar microphysics scheme, they are not the same. Differences lie mainly in the treatment of the ice processes. Therefore, two experiments with ice processes turned off are performed to see if the model behaviour changes. In WRF, instead of turning off the ice process in WSM6, the Kessler warm-rain microphysics scheme (Kessler, 1969) is used for simplicity.

Figure 12 plots $w_{100}$m overlaid with the rain contours in green. UM is shown in the top panels and WRF in the bottom. Comparing with Figure 5, the early evolution of the storms look similar to that in the CONTROL. WRF, like UM, shows two updraughts on the flanks of the initial updraught at $t = 30$ min. By $t = 50$ min, a ring of updraughts, similar to that in CONTROL at $t = 90$ min, is formed. UM shows two completely split storms by $t = 90$ min. However, it is worth noting that without the ice processes, the split storms in UM have started to reorganize as early as $t = 160$ min as opposed to $t = 240$ min in the CONTROL.

To ascertain that the reason for no splitting in WRF is the same as in the CONTROL, we look at the vertical flux of rain in Figure 13a. The winds at $z = 6$ km suddenly turn downward, increasing the downward flux of rain, as in the CONTROL. Ahead of this downdraught, at $x \approx 195$ km, an updraught is seen in the figure that subsequently becomes the part of the updraught-ring seen at
$t = 50 \text{ min in Figure 12.}$ Like in the CONTROL experiment, the source of this downward wind appears to be the winds that turn towards the low-pressure region and converge at $x \approx 192 \text{ km}$ (Figure 13b).

Although the absence of ice processes helps the split storms in UM reorganize early, it is evident that the storm’s qualitative behaviour in its early phase of evolution remains unchanged.

### 3.3 Experiment NORAIN

The convection initiated due to a warm bubble cannot survive long without the rain. However, it is still reasonable to check whether the initial updraught (we do not call it a storm as there is no rain) splits or not before it dies off in the absence of rain. Note that the formation of the liquid clouds is allowed even though the microphysical
processes have been turned off. In WRF, it is achieved by modifying Kessler’s scheme to only allow for saturation adjustment. In UM, this is done by simply turning the microphysics scheme off.

Consistent with the Rotunno and Klemp (1982) findings, the experiments with all the microphysical processes turned off show eventual splitting of the initial updraught in both the models (Figure 14). The initial updraught in UM stays organized until very late (t = 150 min) and only towards the end of the simulation (t = 240 min) does it appear to split completely. The updraughts in WRF, in this case, are relatively weak. Unlike UM, the initial updraught in WRF is already split by t = 150 min before dissipating entirely towards the end of the simulation. The ultimate split in WRF makes it evident that a secondary downdraught is necessary for WRF to avoid the split that is missing in this experiment.

### 3.4 Sensitivity to turbulent mixing length

Convection in the models are known to be sensitive to diffusion (and dissipation) whether it is artificial (e.g. numerical diffusion) or physically based (e.g. turbulence scheme) (Klemp et al., 2015; Tompkins and Semie, 2017). For example, Hanley et al. (2015) found that reducing the mixing length (λ) in UM produced smaller storms that looked similar to the storms in a higher-resolution simulation. To investigate the model’s sensitivity to mixing length, simulations are performed using \( \lambda = \lambda_0/2 \), \( \lambda_0 \) and \( 2\lambda_0 \) where \( \lambda = \lambda_0 \) refers to the model default as used in CONTROL.

The sensitivity of UM simulations to the mixing length is shown in Figure 15. Increasing or decreasing the value of \( \lambda \) has almost no impact on the early (t < 90 min) evolution of the storm. Differences start to appear for \( t \geq 90 \) min. While the original storm still undergoes a split in all the cases, the split updraughts and downdraughts at \( t = 90 \) min are separated the most with \( \lambda = \lambda_0/2 \) and the least with \( \lambda = 2\lambda_0 \). At \( t = 170 \) min, the split storms in the simulation with reduced \( \lambda \) have reorganized (it actually reorganized at \( t = 140 \) min) with a ring of updraughts at the front the same as at \( t = 300 \) min in CONTROL (Figure 11). This early reorganization is due to less damping, which allowed the updraughts along the ring to survive long enough to become a storm and thereby assist in reorganization, as shown in Figure 11.

The simulation with \( \lambda = 2\lambda_0 \) also shows a ring of updraughts at \( t = 170 \) min even though the split storms (note the clear separation of rain contours) are as separated as in CONTROL. Despite the presence of this ring of updraughts, which could have favoured reorganization...
vertical velocity (shaded, m s⁻¹) at z = 100 m for the UM (top) and WRF (bottom) NORAIN experiments [Colour figure can be viewed at wileyonlinelibrary.com]

as in the previous case, the storms stay split (not shown) until t = 240 min, suggesting that these updrafts are not strong enough to support moist convection due to strong damping.

Figure 16 shows w₁₀₀ₚ for WRF for the three values of λ. Unlike UM, the storm’s behaviour in WRF is found to be insensitive to the mixing-length changes, although its morphology appears to be significantly impacted. Those pockets of updrafts and downdraughts inside the large ring of updrafts are more dispersed with reduced λ due to less damping.

The fact that the storm in UM simulations with λ = λ₀/2 reorganized much earlier gives the impression that the splitting can be avoided by reducing it further. However, simulations with λ = λ₀/4 (not shown) do not show any such tendency. Therefore, we gather that even though the simulations are sensitive to the strength of turbulent diffusion, it does not affect the model behaviour concerning the splitting (or non-splitting) of the initial storm.

3.5 Grid resolution sensitivity

Zarzycki et al. (2019) tested model sensitivity to the grid resolutions (Δ) increasing gradually from 4 km to 500 m. The models showed convergence in the storms’ horizontal structure with increasing resolution, but the differences among the models persisted. That is, the models that had split (or non-split) storms in their control experiment (Δ = 1 km) continued to be so at Δ = 500 m.

We repeat the full microphysics experiment with gradually increasing grid resolution from 1 km down to 250 m, halving at each step. UM is also run at Δ = 125 m. Note that the turbulence scheme’s subgrid-viscosity is not fixed in these simulations as was done in Zarzycki et al. (2019), which makes UM more sensitive to the changes in grid resolution as explained next. The mixing length in UM is proportional to the horizontal grid length (i.e. λ ∼ Δx), which implies a reduction in λ by half for a grid refinement by a factor of 2. The same refinement in WRF implies a reduction in λ by 1.6 because of its isotropic (i.e. λ ∼ (ΔxΔyΔz)¹/₃) formulation.

Figure 17 shows w₁₀₀ₚ for UM. The split storms, which reorganized after t = 240 min at Δ = 1 km (Figure 5), have reorganized about 2 hr earlier by t = 150 min at half the resolution. No apparent splitting is noted at Δ = 250 and 125 m. The structure of the storm is considerably different at Δ = 125 m with several small-scale features. Despite the structural differences, the fact that the initial
storm does not split at $\Delta = 250$ and 125 m points towards a consistent model behaviour for $\Delta$ approaching $O(100 \text{ m})$. The path to reorganization (not shown) at $\Delta = 500 \text{ m}$ is the same as in the CONTROL. WRF, on the other hand, shows consistent behaviour at all the resolutions, as demonstrated in Figure 18. Despite an early sign of split at $t = 50 \text{ min}$, just like in the CONTROL, the initial storm in the WRF does not split completely.

It is instructive to look at the convergence of the global quantities in addition to the storm structure. To this end, Figure 19 shows the evolution of the domain-averaged rainfall with the increasing resolution for the two models. Both the models produce a similar amount of rainfall in the first hour of the simulation, but the differences continue to grow in time. Towards the end, WRF produces nearly 4–5 times more rainfall than the UM, which is not surprising given that the squall line in WRF is fully developed by $t = 4 \text{ hr}$ at all resolutions. UM at $\Delta = 125 \text{ m}$ is found to behave considerably differently from the rest. It produces little rainfall in the first hour at this resolution, but it increases at a much faster rate subsequently. As noted earlier, the domain-averaged rainfall in the WRF appears to converge at $\Delta = 250 \text{ m}$. There is no sign of convergence in UM even at $\Delta = 125 \text{ m}$.

3.6  | Model accuracy

UM’s sensitivity to the grid resolution points to its numerical accuracy, which can be assessed through its effective resolution (Skamarock, 2004). Figure 20 shows the mean spectra of vertical velocity for both models. For WRF, $w$ at $t = 4 \text{ hr}$ is used, whereas for UM, $w$ at $t = 6 \text{ hr}$ is used after the updraughts have reorganized. One-dimensional spectra calculated along the $x$-direction are first averaged for each point in the $y$-direction and then averaged over different heights equally spaced at 1 km between $z = 3$ and 10 km.

WRF resolves smaller scales than UM, which was also noted in Jucker et al. (2020). The effective resolution (estimated as the point of departure from the reference spectrum) of WRF is roughly $6\Delta$ when it is around $9\Delta$ for UM. It means that the waves with wavelengths between $6\Delta$ to $9\Delta$ are damped in UM but not in WRF. Noting that damping has significant control over the structure of storms, as discussed previously, it can be argued that the larger effective resolution of WRF aids its ability to maintain a well-organized convective storm, unlike UM. Therefore, it is reasonable to ask if the storm in the WRF would split if it was less accurate.
To check that, we have performed a low-order WRF experiment using the 2nd order Runge–Kutta time-stepping method (as opposed to the third order used so far) with the 3rd order upwind scheme for spatial discretization (as opposed to the fifth order used so far). Results from this low-order WRF experiment are shown in Figure 21. The storm structure stays more-or-less the same as in the CONTROL with no sign of a complete split despite the effective resolution now being more similar to UM (see the blue line in Figure 20).

4 | DISCUSSION

The persistent splitting (non-splitting) of the initial storm in the UM (WRF) CONTROL, NOICE, and various mixing-length experiments suggest that the storm’s initial evolution in the models is unaffected by the ice processes and the magnitude of turbulent diffusion. Whether splitting takes place or not depends on the rain, as demonstrated by the storm’s ultimate split in the WRF NORAIN experiment. The importance of rain is further highlighted by noting that WRF avoids a split by placing the downdraught (D2) at the right place (i.e. ahead of the initial updraught). The same downdraught is relatively weak in UM due to the weak convergence of horizontal winds at the mid-levels.

One plausible argument for a weaker D2 in UM could be that it is not as efficient as WRF in producing rainfall. However, as noted in Figure 19, the total rainfall amount in the UM and WRF CONTROL are quite similar before the split takes place in UM, except the 125 m simulation, which has very different rainfall during the first hour. Furthermore, the UM storm does not split at Δ = 125 m even when the rainfall amount is the lowest, which reaffirms that the location where the rain falls is critical in deciding the model behaviour.

Given that the storm did not split in the lower-order WRF experiment suggests that the model’s formal accuracy is also probably irrelevant in this regard. This argument is supported by the results in Zarzycki et al. (2019), where it is noted that the models that behaved very differently from the rest (CSU, FV³ and TEMPEST) are not necessarily of lower or higher accuracy. The
time integration schemes in CSU and TEMPEST are third-order, whereas it is second-order in FV$^3$. The spatial discretization schemes in these models are also of mixed accuracies.

There are other possibilities that are not considered in this work. The coupling between physics and dynamics is one of them. As both the models behave similar with saturation-adjustment alone (NORAIN) but not when warm-rain microphysics (NOICE) is used together with saturation-adjustment, we suspect the answer lies in the way these two processes interact with each other and with the dynamics. Typically, it is the saturation-adjustment that connects the dynamics and physics in a model. As mentioned in Section 2.1, saturation-adjustment in WRF is performed within the microphysics scheme called at the end of the physics call. In contrast, in UM, it is performed first before the microphysics scheme and then again at the end of the time step. These choices are part of model design and, through the results presented in this article, appear to play a vital role in deciding model behaviour.

5 | CONCLUSION

The splitting of an initial axisymmetric storm in a sheared environment has been studied in the past. The common understanding that emerges from those studies is that under a strongly sheared environment, a low-pressure region develops at the mid-level on the flanks of the initial updraught that produces an upward pressure gradient leading to the ultimate split. The presence of a downdraught can accelerate the splitting processes, but it is not of primary importance. The present work aims to show that splitting can take place even under a weakly sheared environment and whether the storm splits or not is model dependent.

A warm bubble experiment in which an initially axisymmetric temperature bubble leads to forming a fully developed squall line in a few hours has been performed with UM and WRF. The model differences, besides the differences in their dynamical cores, have been kept to a minimum. Several experiments have been performed to
test different model components for their roles in the splitting (or not) of the initial storm. Findings of the present work are summarized below:

1. Contrary to the published results (e.g. Weisman and Klemp, 1982), the initial storm in UM splits within the first hour of the simulation even under a weakly sheared environment. The split storms reorganize after 4 hr to form a mature squall line by \( t = 6 \) hr in the CONTROL experiment. This reorganization takes place...
about 80 min earlier in the absence of ice processes, demonstrating the ice microphysics’ role in the evolution of the squall line. The initial storm eventually splits in the absence of rain processes suggesting that the upward pressure gradient on the flanks of the original updraught, as suggested by earlier studies, is the primary reason for it.

2. The initial storm in WRF also splits into two but only at the lower levels. Results show that a complete split is avoided by forming a secondary downdraught ahead of the initial updraught. The cold pool from this downdraught converges with the oncoming winds at the low levels to help the model generate a ring of updraughts connecting the two updraughts. It is further shown that the secondary downdraught results from an increased (horizontal) wind convergence at the mid-levels that helps produce higher downward fluxes of the hydrometeors, which then convert into the rain.

3. The microphysical processes and turbulent mixing show strong control over the evolution and the storm’s morphology, but they do not change the underlying model behaviour. The split storms reorganize early in UM in the absence of ice processes and reduced mixing length compared to the CONTROL. WRF is found to be insensitive in this regard.

4. Horizontal resolution sensitivity experiments show that both the storm’s horizontal structure and the domain-averaged rainfall in WRF approach convergence with increasing resolution. The storm does not split at any resolution. UM, on the other hand, show high sensitivity to the grid resolution. Neither the horizontal structure of the storm nor the domain-averaged rainfall show convergence even at a grid resolution of O(100 m). However, the storm does not split at Δ = 250 and 125 m suggesting that the splitting at coarser resolutions is a numerical artefact and that a resolution of the order of 100 m is needed to capture the early evolution of the storm adequately.

5. Using the vertical velocity spectra and the results from the lower-order WRF experiment and the results from Zarzycki et al. (2019), it is argued that the formal accuracy of the model has no role in this aspect of model behaviour. We further argue that the key lies in the way dynamics and the warm-rain microphysics in the models are coupled through saturation adjustment.

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