Application of a Global Mesoscale Model for Predicting the Formation of Twin Tropical Cyclones associated with a Madden-Julian Oscillation

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Abstract

Over the past several decades, tropical cyclone (TC) track forecasts have been steadily improving, but intensity and genesis forecasts have lagged behind. One of the major challenges in TC genesis prediction is the accurate simulation of complex interactions across a wide range of scales, from the large-scale environment (deterministic), to mesoscale flows, down to convective-scale motions (stochastic). General circulation models (GCMs) have been used to study TC genesis statistics and inter-annual variability, but their insufficient grid spacing and physics parameterizations are known limiting factors. Recent advances in high-resolution global modeling and supercomputing have made it possible to mitigate some of the aforementioned issues. One of the important questions to be answered is: if and how the lead time for predicted TC formation can be extended? In this study, genesis of two pairs of twin TCs associated with a Madden-Julian Oscillation (MJO) event in May 2002 is investigated by performing 10-day numerical simulations with a global mesoscale model (GMM). Sensitivity experiments are also conducted with different moist convection schemes to understand the aggregate effects of precipitation processes on TC activity. It is found that the model is capable of predicting the genesis of these TCs about two to three days in advance as well as their subsequent movements. Real-data simulations show the transition from larger-scale convectively driven systems to smaller-scale TCs and, therefore, suggest that the lead time for predicting TC formation could be extended with realistic representations and improved simulations of an MJO.

Key words: forecast, twin TC, MJO, global mesoscale model, supercomputing

1. Introduction

Accurately forecasting tropical cyclone (TC) genesis, frequency, intensity and movement is crucial in preventing loss of life and property as well as for studying TC inter-annual variability and the impact of climate change on long-term TC variations. To achieve this goal, we need to improve numerical models to realistically simulate the modulation of mesoscale TC activity by the environmental flows at large spatial- and temporal-scales, and long-term variations of these large-scale flows. Using global models for TC prediction is a natural choice, because these models can simulate multiscale flows globally and thus reduce the errors associated with limited one-way interactions between a TC and its environmental flows in regional numerical models, which are inherited from the usage of the lateral boundary conditions. However, this is very challenging because such a global model would require sufficient resolution to accurately represent fine-scale physical and dynamical processes as well as respond to warm sea surface temperatures (e.g., Bengtsson et al., 2007) and thereby demands tremendous computing resources. Modern supercomputing technology has made it possible to employ ultra-high resolution GCMs (Kerr, 2006) and as a result obtain remarkable short-term forecasts of hurricane track and intensity (e.g., Atlas et al., 2005; Shen et al., 2006a-b). Motivated by the scientific challenge and encouraged by preliminary success in high-resolution global modeling, the objective is to now extend our TC studies from short-term forecasts to climate simulations, beginning with the model's ability to simulate multiple processes and their scale interactions during TC genesis.

Hurricane models, along with guidance from observations, have been used to help construct TC theories since the 1960s. Two major intensification mechanisms (e.g., Lin, 2007) are CISK (conditional instability of the second kind, Charney and Eliassen, 1964; Ooyama, 1964) and air-sea interaction (wind-induced surface heat exchange, Emanuel, 1986), which have had a huge influence on the development and/or improvement of cumulus parameterizations (e.g., Anthes, 2003) and boundary/surface layer parameterizations, respectively. It has been documented that coarse-resolution model simulations are strongly influenced by these parameterizations, which often leads to large errors in track and intensity. Recently, a “vortex merger” mechanism has been proposed for addressing the initial intensification during tropical cyclogenesis (e.g., Hendrick et al., 2004), which states that the merging of small-scale vortices plays an essential role in TC formation. In particular, a moist vortex merger is more efficient than a dry one, producing stronger TC intensities at earlier times. In simulating TC formation with coarse-resolution models, Nolan (1999) suggested that axisymmetrization, instead of "vortex merger", may appear in association with vortex intensification. In contrast to the focus on the small-scale processes that contribute to TC formation, Holland and Webster (2005) emphasized the importance of down-scale energy and vorticity transfer associated with the accumulation of large-scale Rossby-mode waves (Webster and Chang, 1988), which does not involve moist convection. The interaction of mesoscale vortices with a monsoon trough during the formation of TC Oliver (1993) was discussed by Simpson et al. (1997). They hypothesized that these interactions, while stochastic in nature, could have some degree of determinism established by the large-scale flow. Encouragingly, Tory et al. (2006a,b), who conducted shorter-term numerical experiments on a 0.15 degree unstaggered grid with a limited-area model, reported that TC formation can be predicted with a lead time of 24-36 hours without the detailed simulation of small-scale convection. From a modeling perspective, these studies indicate the importance of accurate simulations of the large-scale environment and the (aggregate) feedbacks of small-scale processes on a mesoscale vortex and encourage the use of high-resolution global models to improve the prediction of TC formation. In other words, the lead time for predicted TC genesis could be extended if a model could realistically simulate the evolution of large-scale flows (in the form of a precursor) and their modulation on TC activity as well as the feedbacks by small-scale resolved and parameterized processes. To illustrate this, we begin with a study predicting tropical cyclogenesis associated with a Madden-Julian Oscillation (MJO, Madden and Julian, 1994).

It has been documented that the nearly simultaneous formation of two TCs straddling the equator at low latitudes occasionally may occur in the Indian Ocean and West Pacific Ocean (e.g., Lander 1990). These TCs are called “twins" as they are nearly symmetric with respect to the equator. Previous studies showed that this twin TC activity can be modulated by the eastward propagation of an MJO (e.g., Liebmann et al. 1994; Maloney and Hartmann 2000). Idealized simulations (Ferreira and Schubert 1996; Aiyyer and Molinari 2003) have suggested the importance of westerly wind bursts (WWBs), which are associated with the MJO, in TC formation. In this study, the importance of an MJO in twin TC genesis will be investigated using a GMM with real data to demonstrate the capability of such a model to simulate the transition from larger-scale organized convection to smaller-scale TCs.

2. The Model and Numerical Approach

The GMM, previously called the high-resolution finite-volume GCM (fvGCM), is composed of three major components: 1) finite-volume dynamics, 2) NCAR CCM3 physics, and 3) the NCAR Community Land model (Lin 2004; Atlas et al. 2005; Shen et al. 2006a). Dynamic initial conditions (ICs) and sea surface temperatures (SSTs) are derived from GFS T254 (~55km) analysis data and 1° optimum interpolation SSTs from the National Centers for Environmental Prediction (NCEP). No vortex initialization (e.g., a bogus vortex) is applied in the initial fields. Previous studies with more than sixty 5-day runs have shown the 1/8th degree model with disabled cumulus parameterizations (CPs) was able to produce remarkable hurricane forecasts in 2004 and 2005 (e.g., Shen et al. 2006a,b). This study will discuss 10-day forecasts for two pairs of twin TCs that occurred in May 2002 during a strong MJO event. In order to make the model suitable and feasible for studying TC climate, the focus will be on the model's performance regarding TC genesis rather than its ability to simulate detailed mesoscale processes and their interactions with the large-scale flow, although these may be integral to TC formation (e.g., Simpson et al. 1997). More detailed discussions on the hierarchical multiscale interactions during the formation of TC Nargis (2008) in the Indian Ocean with the GMM can be found in Shen et al. (2010). In this study, most of the simulations are performed with ¼ degree resolution and without CPs. To verify whether simulations of TC formation are sensitive to the choice of particular model moist physics, two parallel experiments are performed with the same initial conditions but different CPs. The first experiment (labeled “exp-A”) follows the original settings but with the Zhang and McFarlane (1995) and Hack (1994) schemes for deep and shallow-and-midlevel convection, respectively. The second experiment (labeled “exp-B”) is performed with the NCEP SAS (simplified Arakawa and Schubert) scheme (Pan and Wu 1995).

3. Numerical Results

In early May 2002, large-scale organized convection associated with an MJO event was observed in the Indian Ocean (Fig. 1a). While the MJO was continuously progressing eastward, six TCs appeared sequentially, including two pairs of twin TCs (Fig. 1b-c) in the Indian Ocean, one typhoon to the west Pacific and one hurricane to the east Pacific. In the following sections, simulations of twin TC genesis with the GMM initialized with analysis data will be discussed (to our knowledge, this is the first such attempt with real-data). The best tracks of these TCs are available from the Joint Typhoon Warning Center and National Hurricane Center and are plotted with black lines for comparison. QuikSCAT seawinds data (Liu et al. 1998), available at a 0.5° resolution, are also used for verification.

3.1 Twin TCs Kesiny (3-11) and 01A (6-10 May)

The TC Formation Alert for Kesiny (2002) in the Southern Hemisphere was issued (re-issued) at 2100 UTC 2 (0600 UTC 3) May (Fig. 2). Kesiny propagated eastward, turned southward, and then moved west-southwestward. By 0600 UTC 6 May, Kesiny's MSLP (minimum sea level pressure) had deepened to 976 hPa, and it maintained its strength until 0000 UTC 7 May. It continued to move west-southwestward and crossed the northern tip of Madagascar on 9 May. The accompanying torrential rains caused severe and widespread flooding. About 520,000 people were adversely affected by Kesiny and 5000 were left homeless. TC 01A, Kesiny's counterpart in the Northern Hemisphere, was first recorded at 1800 UTC 6 May and moved northwestward due to the influence of a sub-tropical ridge to its north. It made landfall near Salalah, Oman at about 0900 UTC 10 May and then weakened afterward. TC 01A was the first storm to hit Salalah in nearly 20 years and caused substantial damage (http://www.australiasevereweather.com/cyclones/2002/summ0205.htm).

Figures 2a-c show a 10-day forecast initialized at 0000 UTC 1 May. Despite the time difference in the formation of these two TCs of about 89 hours, which poses a challenge to predict both, the global model simulates the genesis of TCs Kesiny and 01A at the right locations and times about 45h (54h) and 96h in advance, respectively, successfully simulating the self-amplification process whereby initial weak storms/disturbances grow to become TCs. The subsequent movement for both TCs is also captured reasonably well (e.g., Fig. 4a, which will be discussed in subsection 3.3), including Kesiny's re-curvature on 3-5 May. Compared to the official forecast position errors of TC 01A, the track forecast using a global model is very encouraging. While the average intensity of Kesiny is simulated reasonably well, the intensity of TC 01A is over-estimated after 120h of integration (Fig. 4a), which may be due to the excessive precipitation associated with disabling the CPs. Experiments with different CPs will be discussed for verification below.

3.2 Twin TCs Errol (9-14) and 02B (9-12 May)

The second pair of twin TCs was observed from 9-14 May (Fig. 3). The southern member of the two, Errol, was first named on 9 May north of Cocos Island. During its entire lifetime, Errol meandered within a very limited area between 6.6^{o}S-10.8^{o}S and 94.6^{o}E-97.6^{o}E. TC 02B was first noted near (8.4^{o}N, 95.5^{o}E) at 0600 UTC 09 May. This storm moved northward under the influence of a mid-level ridge to its east. It made landfall at 2300 UTC 11 May south of Yangan near (16.8^{o}N, 96.2^{o}E). To capture the genesis of these storms, a 10-day forecast was initialized at 0000 UTC 6 May. As shown in Figs. 3a-c, the genesis and subsequent movement of TC 02B in the North Indian Ocean are simulated quite well. In contrast, only less-organized convection in the South Indian Ocean, which might be identified as Errol, is simulated during the first 5 days of integration. The genesis of Errol is simulated at a later time with a larger displacement error compared to the other three TCs (e.g., Fig. 5a). In comparison, for the first pair of twin TCs (TC 01A and Kesiny), which appear in the initial conditions, the predicted movement is quite good, although the modeled TC 01A moves slower than was observed. This is very likely due to the vortex spin-up problem. Interestingly, QuikSCAT sea winds revealed TC 01A with an open circulation on 9 May and did not capture TC 02B, which could be due to the known issue of QuikSCAT winds being less accurate near coastal areas.

It is worth mentioning that there is a good agreement between the simulations (Fig. 3b) and satellite imagery (Fig. 1c) for the four major convective events, namely the 4 TCs. However, a false-positive convective event also appears along longitude 80^{o}E, which is discussed below.

3.3 Experiments with different moist schemes

In this subsection, we compare simulated surface winds and precipitation with NASA QuikSCAT winds and TRMM precipitation to address the aforementioned issues, including: (1) the dependence of formation simulations on different moist convection schemes, and (2) the dependence of the false-positive event on the initial conditions and/or moist scheme. In addition, a comparison is made to understand the performance of different moist schemes in simulating the spatial (and temporal) distributions of precipitation, which could be used to understand (3) the model's performance in simulating the regional impacts of a specific weather event (e.g., an MJO in this case).

The spatial distribution of MSLP over the 10-day integration, which is initialized at 0000 UTC 1 May 2002, is shown in Fig. 4 to qualitatively display the initial location and subsequent movement of the simulated TCs. Panels (a)-(c) are results from the control run, exp-A run, and exp-B run, respectively. As discussed earlier, the control run in Fig. 4 simulates the formation and movement of the first twin TCs realistically. In contrast, the exp-A run fails to simulate the genesis of TC 01A (Fig. 4b). Though the exp-B run is able to simulate the formation of TC 01A, it results in slower propagation speeds for both of the twin TCs (Fig. 4c). It is worth noting that a false-positive event clearly appears in the experiments with CPs (Fig. 4b-c) but not in the control run with only the large-scale condensation scheme. Figure 5 is the same as Fig. 4 except for different initial conditions (0000 UTC May 6 2002). Figure 5a for the control run shows realistic predicted movement for the first pair of twin TCs and TC 02B, but the simulated location of TC Errol has a larger error. For the exp-A run (Fig. 5b), an intense false-positive event exists. In contrast, the exp-B run produces a weaker false-positive event (e.g., Fig. 5c and Fig. 6d) but fails to simulate the formation of TC Errol (e.g., with a closed circulation.)

Figures 6a-d show precipitation and surface winds averaged over May 8-11, 2002 using NASA TRMM precipitation (shaded) and QuikSCAT winds (vectors) for the control run, exp-A run, and exp-B run, respectively. The three experiments are initialized at 0000 UTC 6 May 2002. It is important but a challenge to examine the performance of a moist scheme in simulating TC activity at different stages (e.g., initiation, intensification, weakening, etc). During the numerical integrations from May 8-11, these four TCs (i.e., the two pairs of twin TCs) go through different stages of their lifecycles, including first intensification and then weakening for the first pair of twin TCs and initial formation for the second pair of twin TCs. *Therefore, examining the spatial distributions of averaged precipitation during May 8-11 could be very useful for understanding the performance of a specific scheme in simulating the aggregate effects of precipitation processes on TC activity.* In general, for the control run, precipitation is overestimated in the North Indian Ocean and underestimated in the South Indian Ocean. Overall, the simulations with CPs show reduced precipitation, and the simulated movement and formation of these TCs have larger errors. To make a quantitative comparison of the simulated precipitation from different moist schemes over the three-day period (May 8-11), we calculate the average precipitation over four individual 10^ox10^o sub-domains, which are centered on the TRMM precipitation maxima. The average precipitation in these sub-domains (labeled as D1-D4) are associated with TCs 01A, 02B, Kesiny, and Errol, respectively, and are used to illustrate the model's performance in simulating the regional impacts associated with the MJO (and TCs). As shown in Table 1 (the closest values to TRMM are shown in red), the control run with the explicit moist scheme produces the best result over the large domain (25^oS-25^oN; 40^oE-110^oE) and in three of the sub-domains (D1, D2, and D4). The less accurate result in sub-domain D3 reflects the slower propagation speed simulated for TC Kesiny. Overall, parameterized moist processes associated with a specific CP and their non-linear interaction with other physical processes could produce either weaker or stronger precipitation. It is interesting to note that if location errors are not counted (namely, precipitation is averaged over a sub-domain centered on the local precipitation maximum associated with an individual TC), the overall performance of the different schemes in simulating precipitation for these four TCs is comparable (e.g., Table 1). For TC Errol, the average precipitation amount simulated in all three experiments during the period 8-11 May (e.g., Table 1) is underestimated by about 40-50%. However, the control run (exp-A run) is able to simulate the formation and intensification of TC Errol at a later time, as shown in Fig. 5a (Fig. 5b). This suggests that the performance of a specific moist convection scheme over a different period of time should also be examined, which is the subject of a future study.

The appearance of the false-positive convective event (along longitude 80^oE) in all three runs (Figs. 6b-d) suggests that (i) this event may be inherited from the initial conditions, and/or (ii) additional model physical processes for weakening this event are needed.

4. Concluding Remarks:

In this study, six 10-day 0.25^o simulations are presented of cyclogenesis for two pairs of twin TCs that occurred in association with an MJO in May 2002 using a global mesoscale model. Preliminary analyses show that the genesis of 3 of these TCs is reasonably simulated about 2 to 3 days in advance. In addition, forecasts of subsequent TC movement are also accurate. However, the genesis forecast of TC Errol is less accurate; it meandered within a very limited area during its entire life cycle. As the MJO continuously propagated eastward, super-typhoon Hagibis and Hurricane Alma occurred subsequently in the West and East Pacific. Two additional 10-day numerical experiments are initialized at 0000 UTC May 11 and 22 to predict the formation of super-typhoon Hagibis and Hurricane Alma, respectively (not shown). All of the results suggest that the occurrence of a large-scale MJO and its accompanying WWB appears to dictate the location and timing for TC genesis, which as a result could provide a means to obtain deterministic forecasts of TC genesis. However, further analysis on the detailed transition processes among the different scales is still needed. Currently, the hierarchical multiscale interaction during the formation of TC Nargis (2008) associated with an MJO and WWB in the Indian Ocean has been examined (Shen et al. 2010). In sensitivity experiments with different CPs, it is found that the control runs with an explicit large-scale condensation scheme produce the most consistent formation predictions for these TCs, thought more cases are still desired to support this conclusion.

Based on the current results, it can be stated that improving long-term simulations of the MJO with high-resolution GCMs could enhance the ability to predict TC genesis. Short-term TC track and intensity simulations with GCMs do not address TC genesis issues in general, and long-term TC climate studies do not emphasize the accuracy of TC genesis at small temporal and spatial scales (e.g., the timing and location of TC genesis). Advances in modern supercomputing technology could help to speedup global model development and to bridge the “gap" between the former and the latter.

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Table 1: Domain averaged precipitation (mm/day) for the large domain (LD, 25°S-25°N : 40°E-110°E), and 10°x10° sub-domains centered on (13°N, 57°E; D1), (9.5°N, 95.5°E; D2), (15°S, 51°E; D3) and (6.5°N, 97.5°E; D4). D1-D4 are chosen based on the TRMM precipitation maxima. D1m-D4m are the sub-domains centered on the local precipitation maxima associated with each of the four TCs.

	TRMM	cntl	exp-A	exp-B
LD	5.5	5.73	6.11	5.98
D1	12.92	15.26	9.41	16.12
D2	29.56	30.7	30.77	22.34
D3	28.96	17.25	11.52	19.14
D4	24.26	12.42	12.97	11.59
D1m	12.92	25.72	16.77	26.73
D2m	29.56	30.7	30.77	22.12
D3m	28.96	18.17	16.2	23.22
D4m	24.26	14.84	13.74	17.4

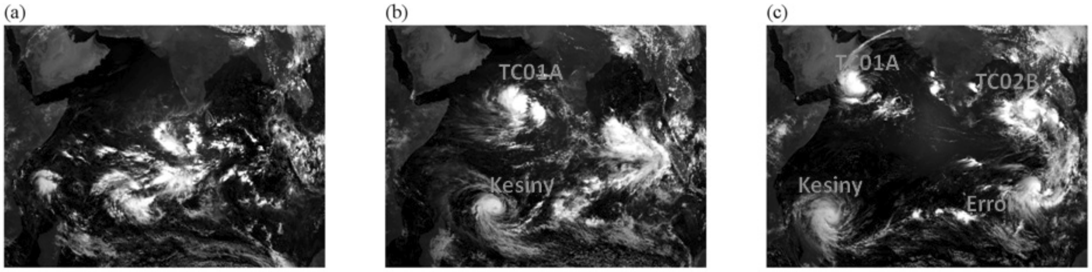

Figure 1: MJO-organized convection over the Indian Ocean at 0630 UTC 1 May 2002 (a). When the MJO moved eastward, two pairs of twin TCs appeared sequentially on 6 May (b) and 9 May (c). See also Moncrieff et al. (2007).

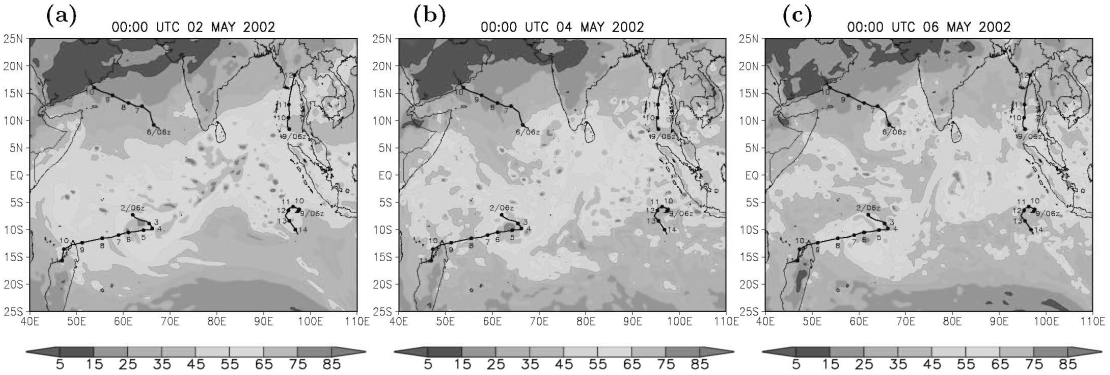

Figure 2: Simulations of total precipitable water (TPW, kg/m^2) from the run initialized at 0000 UTC 1 May 2002 showing the genesis of twin TC Kesiny and 01A. Panels (a)-(c) display simulated TPW at Day 1, 3, and 5, respectively. The best tracks with marks at 0600 UTC are plotted with black lines.

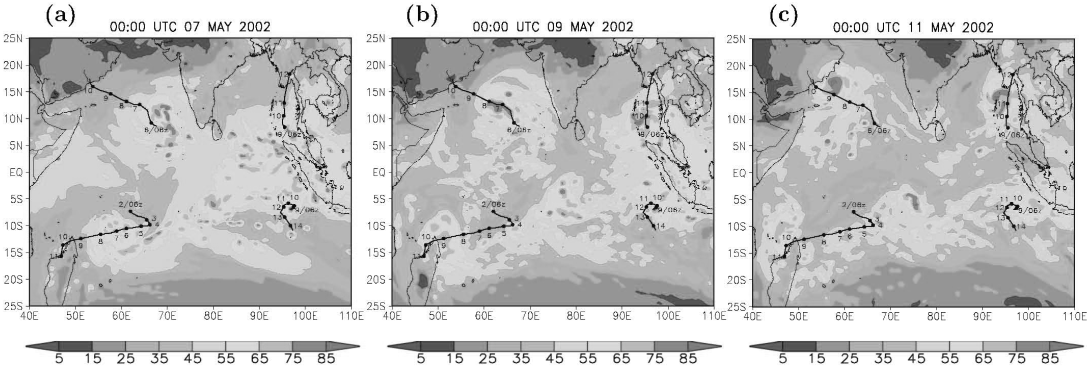

Figure 3: Simulations of total precipitable water (TPW, kg/m^2) from the run initialized at 0000 UTC 6 May 2002 showing the genesis of twin TC Kesiny and 01A. Panels (a)-(c) display simulated TPW at Day 1, 3, and 5, respectively. The best tracks with marks at 0600 UTC are plotted with black lines.

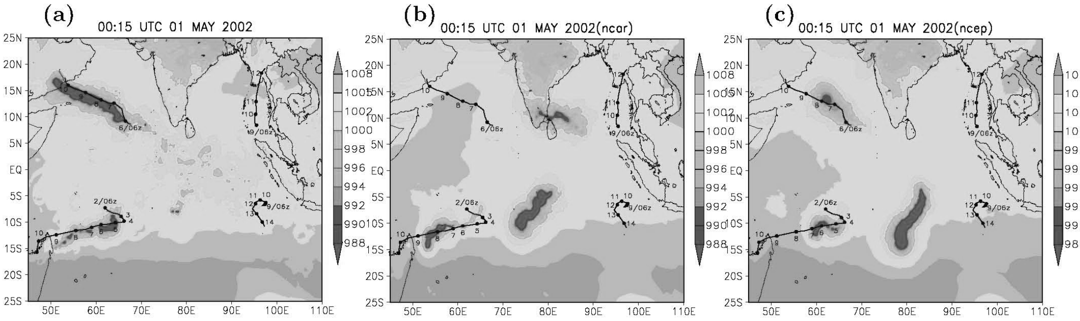

Figure 4: Sensitivity experiments with different schemes for moist processes. The spatial distribution of MSLP over the 10-day integration, which is initialized at 0000 UTC 1 May 2002, qualitatively shows the initial location and subsequent movement of the simulated TCs. (a) the control run, (b) the run with the Zhang and McFarland scheme, and (c) the run with the NCEP SAS scheme.

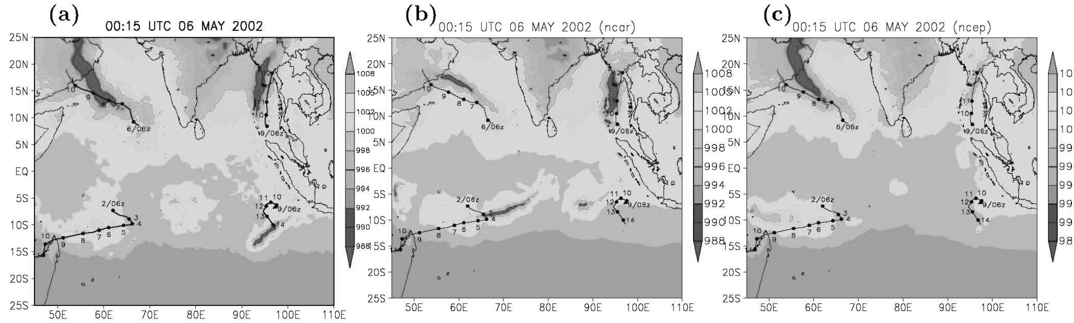

Figure 5: Sensitivity experiments with different schemes for moist processes. The spatial distribution of MSLP over the 10-day integration, which is initialized at 0000 UTC 6 May 2002, qualitatively shows the initial location and subsequent movement of the simulated TCs. (a) the control run, (b) the run with the Zhang and McFarland scheme, and (c) the run with the NCEP SAS scheme.

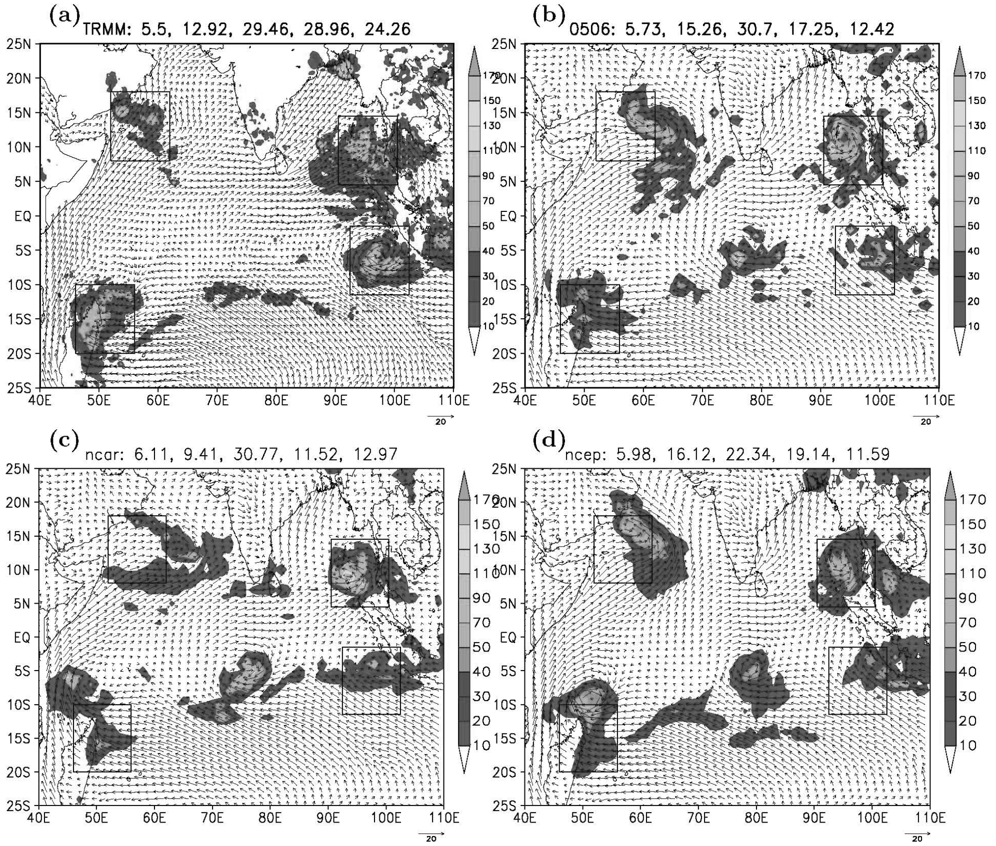

Figure 6: Precipitation (mm/day) averaged over May 8-11, 2002 from (a) NASA TRMM (shaded) and QuikSCAT winds (vectors), (b) the control run (initialized at 0000 UTC May 6) and two parallel runs with different cumulus parameterizations for (c) the exp-A run and (d) the exp-B run.