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High-Resolution Simulation of a Tornado in Bangladesh on 13 May 1996

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High-Resolution Simulation of a Tornado in Bangladesh on 13 May 1996

An honors thesis presented to the
Department of Atmospheric and Environmental Sciences,
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and
graduation from The Honors College

Katy Hollinger

Research Advisor: Ross A. Lazear, M.S.

May 2020

Abstract

The country of Bangladesh has been known to experience some of the deadliest tornado outbreaks in the world. The severe weather season in this region only spans from late March to early May, but can produce significant severe weather outbreaks in that short time. Even with these outbreaks occurring, there has not been extensive analysis completed to evaluate the environmental parameters on these tornado event days in this region.

The goal of this project is to use a Weather Research and Forecasting (WRF) model simulation to evaluate a significant tornado that occurred in the Tangail and Jamalpur districts in Bangladesh on 13 May 1996. This tornado killed an estimated 700 people and caused an additional 32,000 injuries, according to a report from Hosen and Jubayer (2016). With limited surface observations available for this event, a WRF simulation allows for a deeper understanding of the storm and further evaluation of the ingredients that lead to its development. Moisture and thermodynamic variables were evaluated to help diagnose the pre-convective environment, as well as mesoscale boundaries that led to supercell initiation.

Acknowledgements

I would like to thank my advisor, Ross Lazear, for all of his support throughout my undergraduate career and especially throughout the research process. Ross has always been supportive and encouraged me to think creatively about the research questions asked as well as any troubleshooting needed along the way. He has been incredibly helpful, and this project would not be where it is today without him. Ross has also been a huge support in helping me apply to and decide on a graduate school. Thank you!

I would also like to thank all of the professors in my department for the knowledge they have shared with me throughout my undergraduate career, and all of my classmates for being supportive and uplifting throughout this research process.

I would also like to thank my parents and my siblings for their continuous support and encouragement throughout my undergraduate career. They have always pushed me to work hard for my dreams and I would not be where I am today without their love and support.

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I. Introduction

Some of the deadliest tornadoes in the world have occurred in Bangladesh. According to a study by Fujita (1973), parts of Bangladesh experience some of the strongest tornadoes in the world, ranked as F-4 on the Fujita-Pearson (FPP) scale. The only other country identified in this study with greater than F-3 strength tornadoes was the United States. The severe weather season in Bangladesh spans from March to May every year, and the country experiences 6.4 tornadoes per year on average (Paul 2004). Bikos et al. (2016) recognized that this time of year is favorable for tornadoes as a result of low-level moisture from the Bay of Bengal, hot and dry air advected eastward from the Indian Subcontinent, and strong mid-to-upper level flow allowing for directional wind shear across the region.

On 13 May 1996, these characteristics combined to produce a deadly tornado that took the lives of over 700 people and injured an additional 33,000 throughout the districts of Jamalpur and Tangail in Bangladesh (Figure 1) (Paul 1998). Strong reflectivity echoes appeared on the local radar at 1500 Bangladesh Standard Time (0900 UTC) (Schmidlin and Ono 1996). The tornado traveled south-southeast through the Tangail district of Bangladesh, destroying 17,000 houses and earning an F-4 rating (Paul 1998). Along with damage from a tornado, there were also reports of softball-sized hail in the region before the tornado reports occurred (Schmidlin and Ono 1996).

While tornadoes in Bangladesh have been some of the deadliest in the world, minimal research has been done to analyze the environmental conditions that exist prior to tornado development. Analysis of past cases is made more complicated due to limited surface observations and tornado reports not being formally documented (Bikos et al. 2016). With this in mind, the goal of this project is to simulate the deadly tornado event of 13 May 1996 using the

Weather Research and Forecasting (WRF) model to get a better understanding of the environmental conditions that were present in Bangladesh on that day. A wide variety of studies have identified environmental parameters relating to moisture, temperature, and wind as important features to differentiate between non-supercell and supercell thunderstorm formation (Rasmussen and Blanchard 1998, Markowski et al. 2003). Specifically relating to tornadic and non-tornadic supercells, Parker (2014) and Thompson et al. (2003) each established that high values of low-level relative humidity and thus low lifting condensation levels, along with low-level vertical wind shear and high values of convective available potential energy, were significant factors in differentiating between these respective environments. These parameters, along with a lifting mechanism, were evaluated and identified for the tornado event of 13 May 1996.

A similar study was done by Bikos et al. (2016) in which ten significant tornado events were simulated in WRF using the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-Interim Global Reanalysis dataset. Environmental conditions present in these ten cases were averaged and then compared to values that exist over the United States. The 13 May 1996 tornado case was used as one of the ten simulations. Bikos et al. (2016) found that the severe weather characteristics described by Thompson et al. (2003) and Parker (2014) in the United States, including high CAPE values, large deep-layer shear, and low LCL height, were also present in significant tornado events across Bangladesh. This study aims to verify and visualize the results that Bikos et al. (2016) found within a ten-event composite, and analyze those results using observations and a high-resolution simulation for the single event on 13 May 1996.

II. Data and Methodology

Multiple Bangladesh tornado events were analyzed for their synoptic-scale characteristics before one was chosen as the representative case to be simulated. For this synoptic-scale analysis, the Climate Forecast System Reanalysis (CFSR) dataset was used to create upper-level diagnostic plots. Plots created include: 250-hPa height and wind; 500-hPa height, wind, and vorticity; 925-hPa winds, frontogenesis, and temperature advection; and 1000-hPa wind, dewpoint temperature, and mean sea level pressure. Archived observed soundings from the University of Wyoming were also used to get an initial analysis of the conditions present for Dhaka and Calcutta at 0000 and 1200 UTC 13 May 1996.

The Weather Research and Forecasting (WRF) Advanced Research WRF (ARW) model version 4.0 (Skamarock et al. 2008) was used to simulate the tornado event on 13 May 1996. The simulation was initialized at 0000 UTC on 13 May 1996 using the CFSR dataset and terminated 24 hours later at 0000 UTC on 14 May 1996. A double-nested domain was used for this simulation. The horizontal grid spacing of the outer domain was 27-km, while the horizontal grid spacing of the nests were 9-km and 3-km. The grid dimension of the outer domain was 225 x 175 points, while the dimensions of the nests were 250 x 250 points and 271 x 226 points, respectively. This experiment used 28 vertical levels for all domains. Both nests were initialized at the same time as the parent model, 0000 UTC 13 May 1996. The three domains are displayed in Figure 2.

This simulation made use of the Thompson Scheme (Thompson et al. 2008) for the microphysics parameterization, the Mellor–Yamada–Janjic Scheme (MYJ) (Janjic 1994) as the planetary boundary layer physics option, and the Noah Land Surface Model (Tewari et al. 2004) for all three domains. The Kain–Fritsch (Kain 2004) cumulus parameterization scheme was used for the outermost domains, and no cumulus parameterization scheme was used for the innermost domain in order to enable convection-allowing details to unfold. Output from the innermost domain (3km) was generated every 30 minutes, and it was used to enable visualization of mesoscale details such as temperature, dewpoint temperature, wind, convective available potential energy (CAPE), storm-relative helicity, and reflectivity.

III. Results

a. Synoptic Scale Analysis

Before analyzing the mesoscale features of the 13 May 1996 tornado event, it is important to analyze the larger scale synoptic-scale environment. In the 24-hours leading up to the event, a 250-hPa trough moved overhead of Bangladesh and then slightly east by 0600 UTC, leaving Bangladesh just upstream of the base of the trough (Figure 3). By 0600 UTC 13 May 1996, central Bangladesh was also situated in the right exit region of the 250-hPa jet streak. This region supports downward vertical motion, not the upward vertical motion needed to assist in forcing for storm development. Having the base of the trough almost directly overhead, and its associated colder temperatures, would add instability to the region, so it may be that the trough is more indicative of steepening lapse rates, rather than acting as a lifting mechanism.

The 500-hPa height and vorticity were also evaluated to identify any regions of positive vorticity advection by the winds, as that would force upward vertical motion for the system. At 0000 UTC 12 May, there was a vorticity maximum along the Himalayas just to the north and west of Bangladesh (Figure 4). The winds did not appear to be advecting the positive vorticity into the region at this time. The positioning of the trough also aligned well with the 250-hPa trough, and Bangladesh was positioned beneath the base of the trough at this time, potentially adding instability at the 500-hPa level as well. The vorticity maximum then travelled east along with the trough and was just north of Bangladesh by 1200 UTC 12 May. There continued to be a weak stream of positive vorticity along the Himalayas at 0000 UTC 13 May, some of which was associated with the steep slope of the terrain, and by 0600 UTC 13 May, it had strengthened slightly again. At this time, there was not any obvious positive vorticity advection by the winds into Bangladesh, but there was some weak positive vorticity advection just north and east of Bangladesh. This feature may have provided the forcing for the early convection that occurred across northeast Bangladesh, but did not appear to provide direct synoptic-scale forcing for the 13 May 1996 tornado.

Additionally, forcing from temperature advection and frontogenesis were also evaluated to see if they had any impact on the event. Figure 5 depicts 925-hPa temperature advection and 925-hPa frontogenesis. At 0000 UTC 13 May, there was a strong region of warm air advection over northwest Bangladesh, which is a forcing mechanism for upward vertical motion. There was a small region of weak frontogenesis at the same time over northern Bangladesh. By 0600 UTC, as the event time approached, the region of warm air advection weakened and moved over eastern Bangladesh, displacing the forcing for upward vertical motion east of the reported tornado location. This region of warm air advection was co-located with a region of slightly stronger frontogenesis, which also aided in upward vertical motion east of where the tornado occurred.

Imagery from GMS-5 (Himawari-5) from the GIBBS Satellite archive is shown in Figure 4. Imagery from 0530 UTC 13 May showed convection occurring north and east of Bangladesh, in the region of positive vorticity advection previously discussed, while convection over central Bangladesh did not appear until the 0830 UTC image. In both images, there was little to no cloud cover over western Bangladesh and eastern India. This clearing was likely due to the very hot and dry air that existed over this region that, as it advanced to the east, interacted with the southerly moist air from the Bay of Bengal to create the dryline boundary across central Bangladesh. The GIBBS satellite imagery was used as a reference to compare reflectivity plots from the simulation to reality. Bikos et al. (2016) acknowledged that the outflow boundary from the convection over northeast Bangladesh earlier in the day may have been a forcing mechanism for the convection that produced the tornado on 13 May 1996.

b. WRF Mesoscale Features

The end-product of the methods outlined in Section 2 provided a detailed view of the mesoscale environment for the 13 May 1996 tornado event in Bangladesh. Figure 7 depicts the 2-m dewpoint temperature and 10-m wind barbs at 0800 UTC on 13 May 1996, and Figure 8 depicts the near-surface temperature and 10-m wind barbs for the same time. 0800 UTC was used as it was the closest hour prior to the onset of convection in the model. There was a strong moisture and temperature gradient present across Bangladesh on this day, as dewpoint temperatures ranged from 4°C over western Bangladesh to 24°C over eastern Bangladesh, and temperatures ranged from 40°C over western Bangladesh to 32°C over eastern Bangladesh. The hot, dry air that existed at the surface over western Bangladesh was advected eastward from eastern India, where dewpoint temperatures reached as low as 0°C. The warm, moist air over eastern Bangladesh was advected northward from the Bay of Bengal. This strong moisture gradient, coupled with the strong temperature gradient, was associated with a dryline that acted as the forcing mechanism for this tornado event. This dryline was similar to those that occur in the Great Plains of the United States, as it formed at the confluence zone of a moist, maritime airmass and a dry, continental airmass (Parsons et al. 1991, Owen 1996, Schaefer 1974). The dryline in Bangladesh also had the winds ahead of it roughly parallel to the boundary (southerly flow) and the winds behind it roughly perpendicular to the boundary (westerly flow), similar to the drylines seen in the Great Plains (Fujita 1958).

Thompson et al. (2003), Parker (2014), and Bikos et al. (2016) noted that along with having high values of low-level moisture, tornadic supercell environments also need to have high CAPE values and low-level vertical wind shear present. Figure 9 below depicts the CAPE values present at 0800 UTC 13 May 1996. Values of CAPE across eastern Bangladesh, ahead of where the dryline feature evolved, had CAPE values as high as 5600 J kg^{-1}. To analyze the low-level vertical wind shear, Figure 10 depicts the 0-3 km storm relative helicity (SRH) values for 0800 UTC on 13 May 1996. High values of 3-km SRH were present to the south and east of the dryline, with peak values reaching as high as 350 m^2 s^{-2}. These parameters can also be visualized using a model-derived sounding (Figure 11) for a location (labeled as the red dot in Figure 12) ahead of the dryline at 0800 UTC 13 May 1996. The low-level wind profile depicted in the sounding had winds veering with height between the surface and about 750-hPa. This can also be seen in the clockwise-turning hodograph inset on the top-right corner of the Skew-T. The winds at the surface were south-southeasterly, advecting moisture from the Bay of Bengal northward, and were north-northwesterly by 750-hPa. At the surface, the temperature was about 35°C while the dewpoint was about 24°C, highlighting that warm, moist region ahead of the dryline. The winds throughout the lower-to-middle troposphere were west-northwesterly, advecting the hot, dry air from the Indian Subcontinent to Bangladesh. An elevated mixed layer can be seen in the low-to-mid-troposphere as a result of this advected airmass. This elevated mixed layer steepened the lapse rates throughout the troposphere, and with no cap present in the sounding, a surface parcel would be able to accelerate quickly upward upon reaching saturation, showing evidence of significant CAPE in this region as well.

With the aforementioned synoptic- and mesoscale features in mind, it is important to see how they interacted to form convection on 13 May 1996. Figure 13 below depicts 1-km above ground level (AGL) simulated reflectivity present across Bangladesh starting at 0830 UTC 13 May 1996 – the initial onset of convection from the simulation – and ending 1000 UTC 13 May 1996. At 0830 UTC, there is already convection located over northeast Bangladesh, which can also be seen in the observed satellite imagery (Figure 6). Additional convection with low reflectivity values was also initiating right along the region of the dryline feature, that was present on the 0800 UTC images described above, at this time. This region also had extremely high CAPE values (up to 5600 J kg^{-1}) and 0-3km SRH (up to 350 m^2 s^{-2}). By 0900 UTC, the convection along the dryline intensified and moved southeast toward the coastline. At 0930 UTC, the convection intensified more and developed into a line of storms that continued its advance to the south and east. Finally, by 1000 UTC, the convection continued to move south and east and maintain its strength and linear structure. After this time, the convection began to dissipate and weaken as it moved offshore (not pictured). It is important to note, however, that the location of the reported tornado, depicted as the star in Figure 1, is not co-located with the location where the simulated convection initiated or passed over. The distance between the observed tornado and the convection initiation was about 75 km (about 47 miles). While it is important that the model captures the best possible representation of the storm, the overall purpose of this project was to analyze the mesoscale environment present on 13 May 1996, so this fairly small difference in location was not seen as a hindrance to the evaluation of environmental conditions.

IV. Conclusions

The environmental conditions present for the tornado event of 13 May 1996 in the Jamalpur and Tangail Districts of Bangladesh were evaluated using a WRF-ARW model simulation. Surface observations are limited in this region, so a model simulation allows visualization of characteristics that otherwise would be difficult to evaluate. Conditions such as low-level moisture, CAPE, and low-level wind shear were identified by Thompson et al. (2003) and Parker (2014) as important features necessary to differentiate tornadic supercells from non-tornadic supercells. On 13 May 1996, a strong moisture gradient existed across the country with dewpoint temperatures in western Bangladesh as low as 4°C, while to the east, dewpoints were as high as 24°C as southerly flow from the Bay of Bengal increased the environmental moisture levels. This moisture gradient, or dryline, acted through low-level convergence as the major forcing mechanism for convection in this model simulation. The region ahead of the dryline also exhibited CAPE values as high as 5600 J kg^{-1} and SRH values as high as 350 $m^2 s^{-2}$. A model sounding for a location ahead of the dryline showed winds veering with height between the surface and 750-hPa, and a clockwise turning hodograph, indicating decent vertical wind shear in the lower troposphere. The lapse rates throughout the troposphere were also relatively steep due to an elevated mixed layer advected from the Indian Subcontinent, and with no cap present, a parcel lifted from the surface would have had plenty of buoyancy and accelerated upward quickly. The environment ahead of the dryline aligns with the environment that Parker (2014) and Thompson et al. (2003) described as being conducive for tornadic supercell development. While the conditions were present in Bangladesh, they were displaced more to the southeast in the model simulation than where the tornado was reported to occur. Even with this location discrepancy, it is still believed that this model simulation is a good representation of the environment that created the deadly tornado in Bangladesh on 13 May 1996.

The synoptic-scale forcing for this event was minimal, as Bangladesh was situated just upstream of a 250-hPa trough, and there was 500-hPa positive vorticity advection over northeast Bangladesh, but not over the location of the reported tornado. There was also weak 925-hPa warm air advection over northeast Bangladesh that may have supported initiation of the convection there, but it was not a forcing mechanism for the convection that occurred across central Bangladesh. While the trough overhead did not act as a lifting mechanism, the lower heights and colder temperatures aloft were indicative of steep lapse rates in the upper atmosphere, adding to the buoyancy of a parcel lifted from the surface and increasing the CAPE values.

Even with the simulated environment closely aligning with previous literature on tornado environments, the reflectivity in the WRF simulation did not align with the satellite imagery from 13 May 1996. While the simulation did produce strong reflectivity signatures, the location of the convection was displaced to the southeast of where the tornado occurred, in the same region that the high CAPE values and strong low-level shear occurred. The distance between where the tornado occurred and where the simulated convection occurred was approximately 75 km (about 47 miles). While this difference is not huge, it is important to address the discrepancy. Bikos et al. (2016) mentioned that the convection in northeast Bangladesh earlier in the day created an outflow boundary that, when it interacted with the dryline, enhanced lift, and created the storm that produced the tornado that moved through the Jamalpur and Tangail Districts. One explanation for the reflectivity displacement could be that this simulation did not accurately develop the earlier convection and its associated outflow boundary, so the forcing for the simulated convection may have resulted only from the dryline. The model was initialized at 0000 UTC 13 May 1996, and the convection over northeast Bangladesh was already present on satellite imagery by 0530 UTC. Convection occurring this close to the model initialization time may not have given the model enough time to process the environmental conditions and develop the convection accurately. Without the convection occurring in the correct region or at the correct time, the outflow boundary likely did not interact with the dryline at the same location, if it interacted at all.

While the purpose of this project was to analyze the environmental characteristics present during the 13 May 1996 tornado, which did not require the convection to be perfectly simulated, it is important to recognize some additional reasons this model may not have accurately depicted the location of the convection. The initialization dataset that was used was the CFSR, as previously mentioned. The choice of this dataset, as opposed to the ERA5 or the Global Forecast System (GFS), may have impacted the resulting environment that was produced and its associated convective initiation. Each dataset has a different resolution and reanalysis that could produce a different result. Future work may include evaluating these conditions using different initialization datasets and initializing the model at an earlier time in order to depict the interaction between the dryline and the outflow boundary more accurately. Analyzing other known tornado event days may occur in order to compare the resulting environmental conditions that interact to create the powerful and deadly tornadoes that occur in Bangladesh.

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Figures

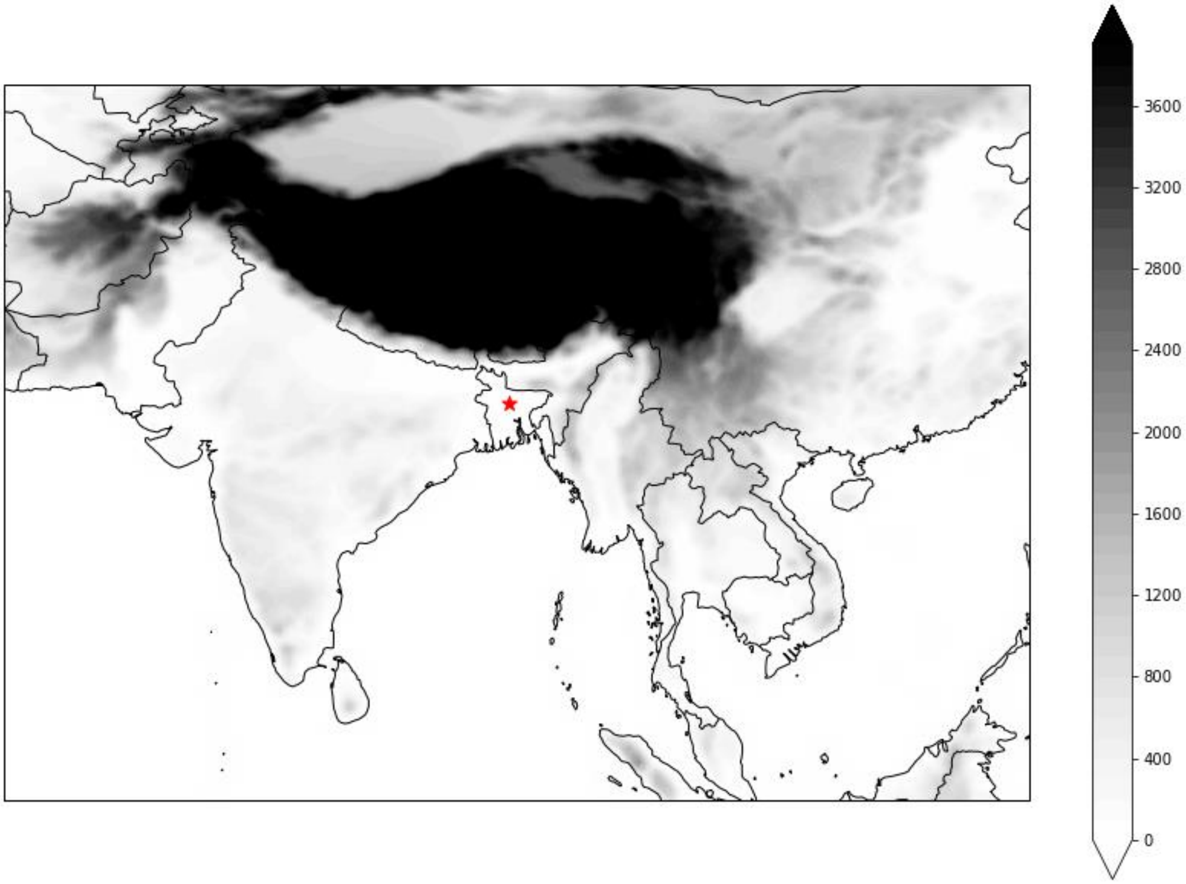

Figure 1. Map of southern Asia with topography in the fill. The red star represents the location of the reported tornado in Bangladesh on 13 May 1996.

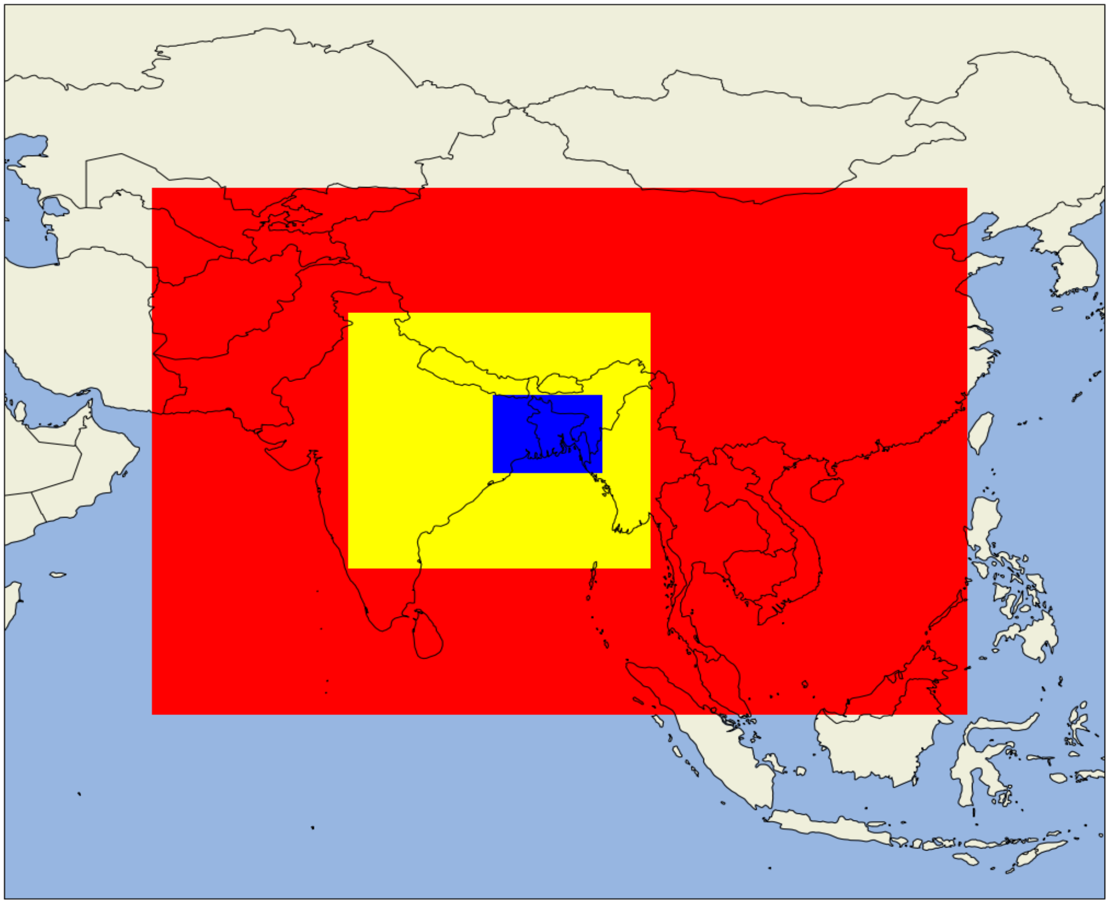

Figure 2. Domains used in WRF-ARW simulation. Outer domain (27-km) is in the red fill, second domain (9-km) is in the yellow fill, and innermost domain (3-km) is in the blue fill.

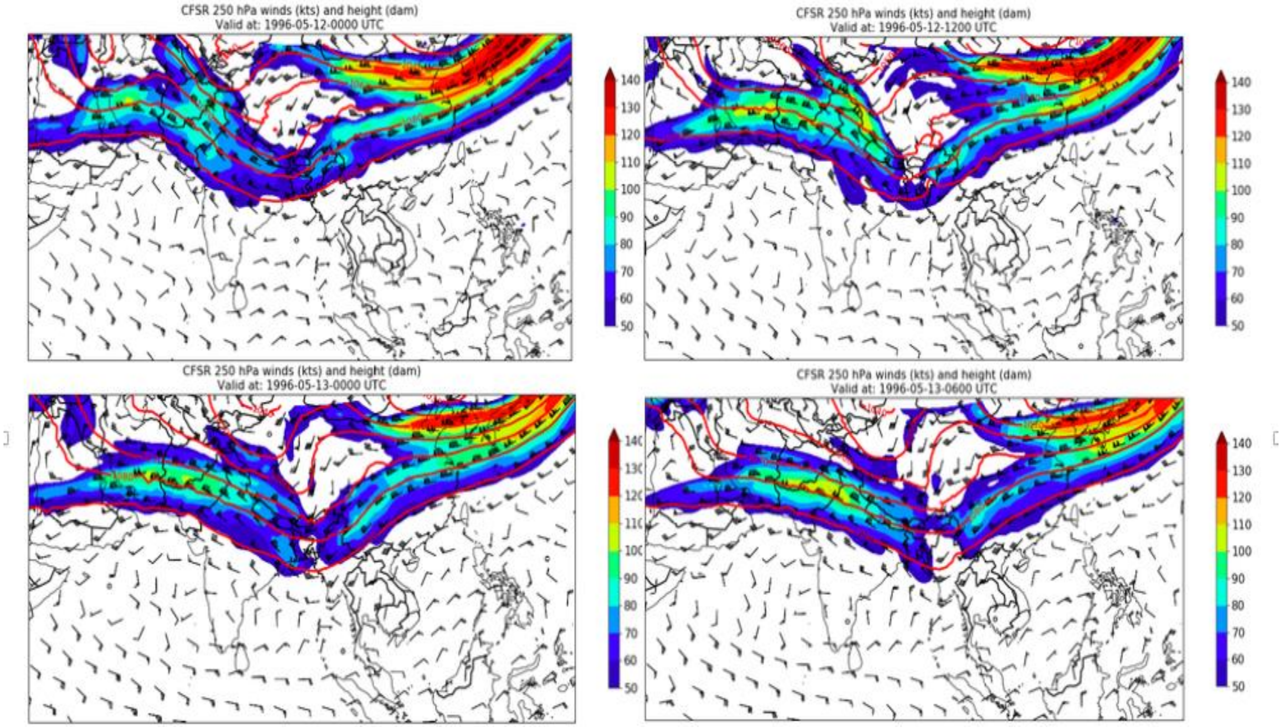

Figure 3. CFSR 250-hPa geopotential height (decameters, contoured red) and winds (knots, color fill) across Southeast Asia. Plots are for 0000 UTC 12 May 1996 in the top left, 1200 UTC 12 May 1996 in the top right, 0000 UTC 13 May 1996 in the bottom left, and 0600 UTC 13 May 1996 in the bottom right.

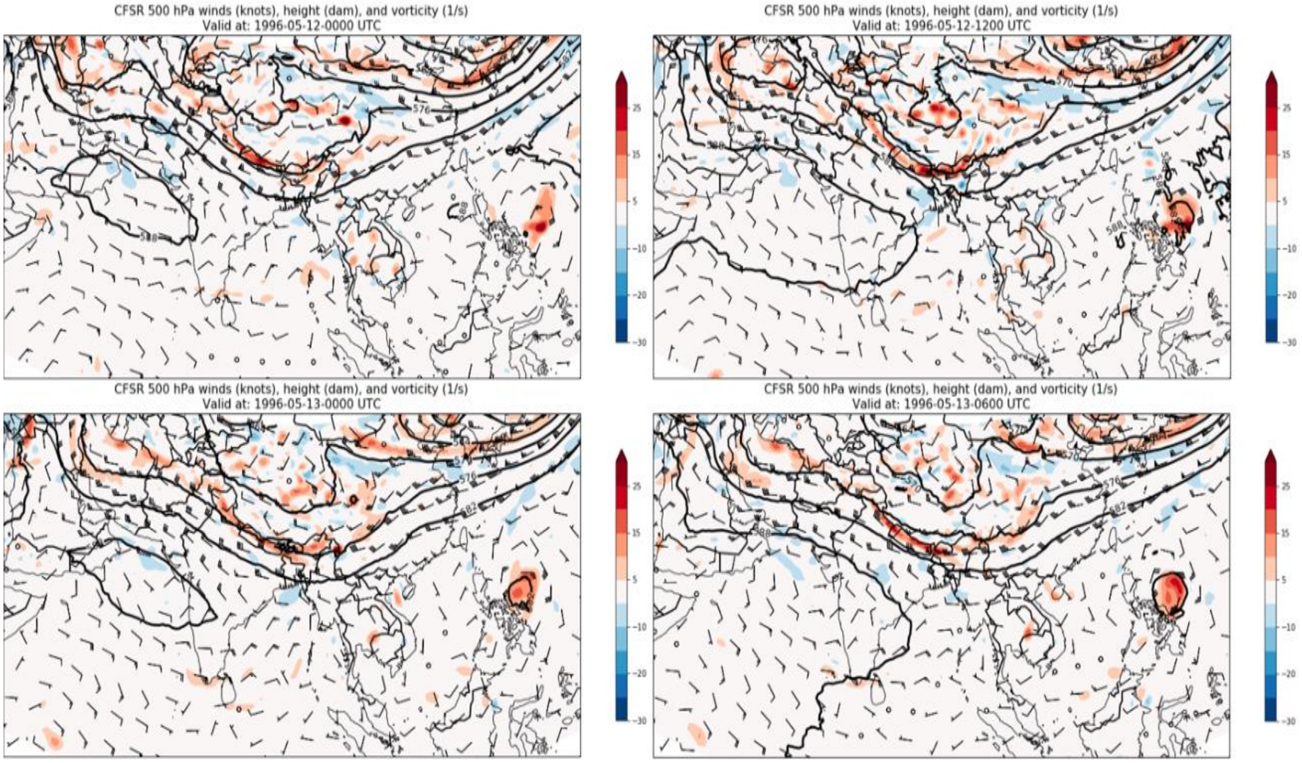

Figure 4. CFSR 500-hPa geopotential height (decameters, contoured black), winds (knots, barbs), and vorticity (s^{-1} x 10^{-5}, color fill). Plots are for 0000 UTC 12 May 1996 in the top left, 1200 UTC 12 May 1996 in the top right, 0000 UTC 13 May 1996 in the bottom left, and 0600 UTC 13 May 1996 in the bottom right.

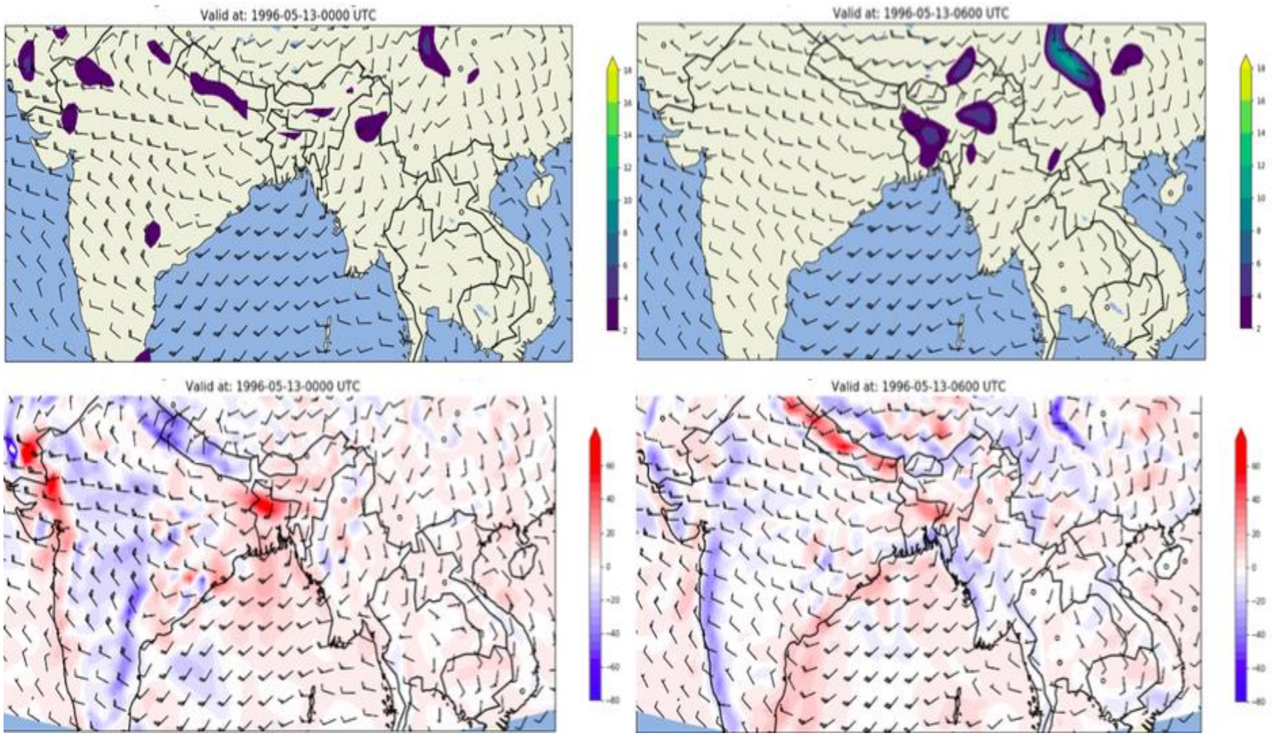

Figure 5. CFSR 925-hPa winds (knots, barbs), frontogenesis (K $3h^{-1}$ 100 km^{-1}) in the fill on the top two panels, and temperature advection (K s^{-1} x 10^5, color fill) in the fill on the bottom two panels.

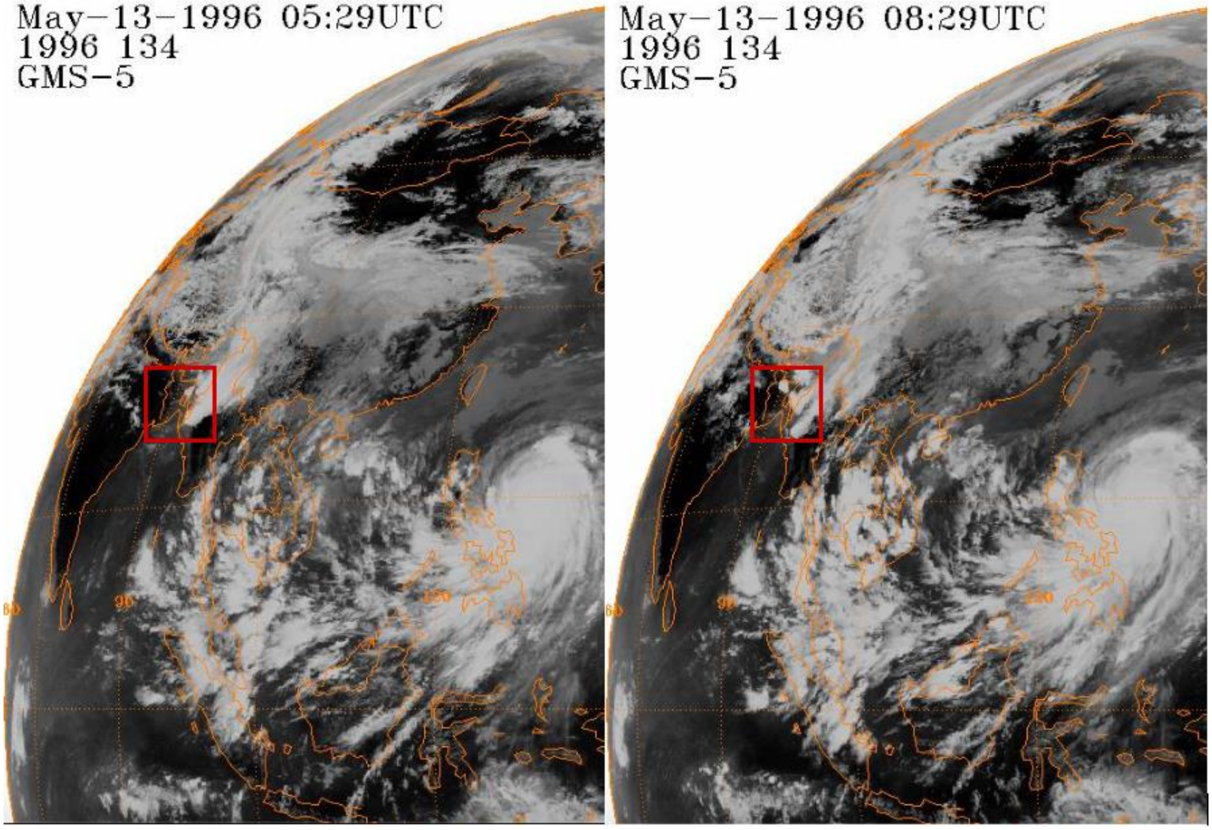

Figure 6. Infrared satellite imagery from GMS-5 (Himawari-5) for 0530 UTC 13 May 1996 (left) and 0830 UTC 13 May 1996 (right). Bangladesh is indicated with a red box. From https://www.ncdc.noaa.gov/gibbs/

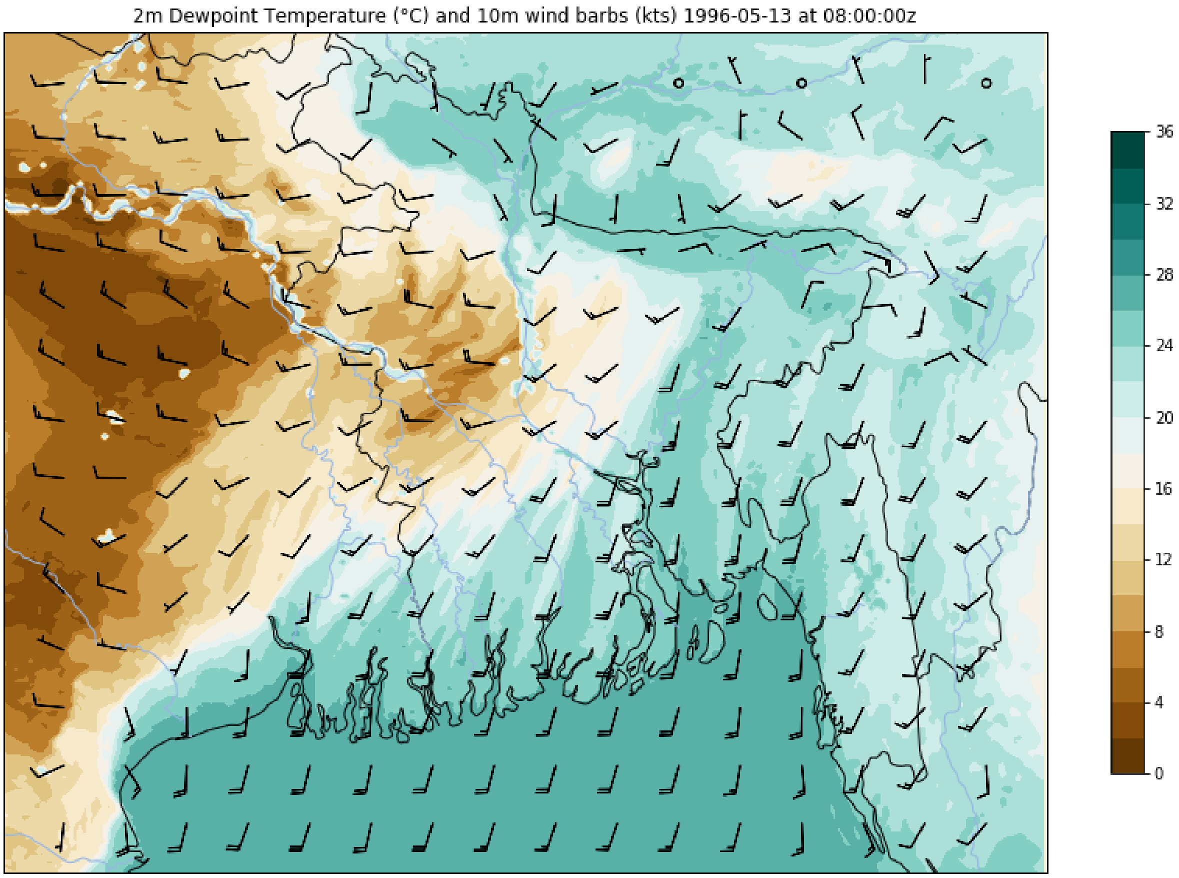

Figure 7. 2-m dewpoint temperature (°C, color fill) in the fill and 10-m wind (knots, barbs) over Bangladesh for 0800 UTC 13 May 1996.

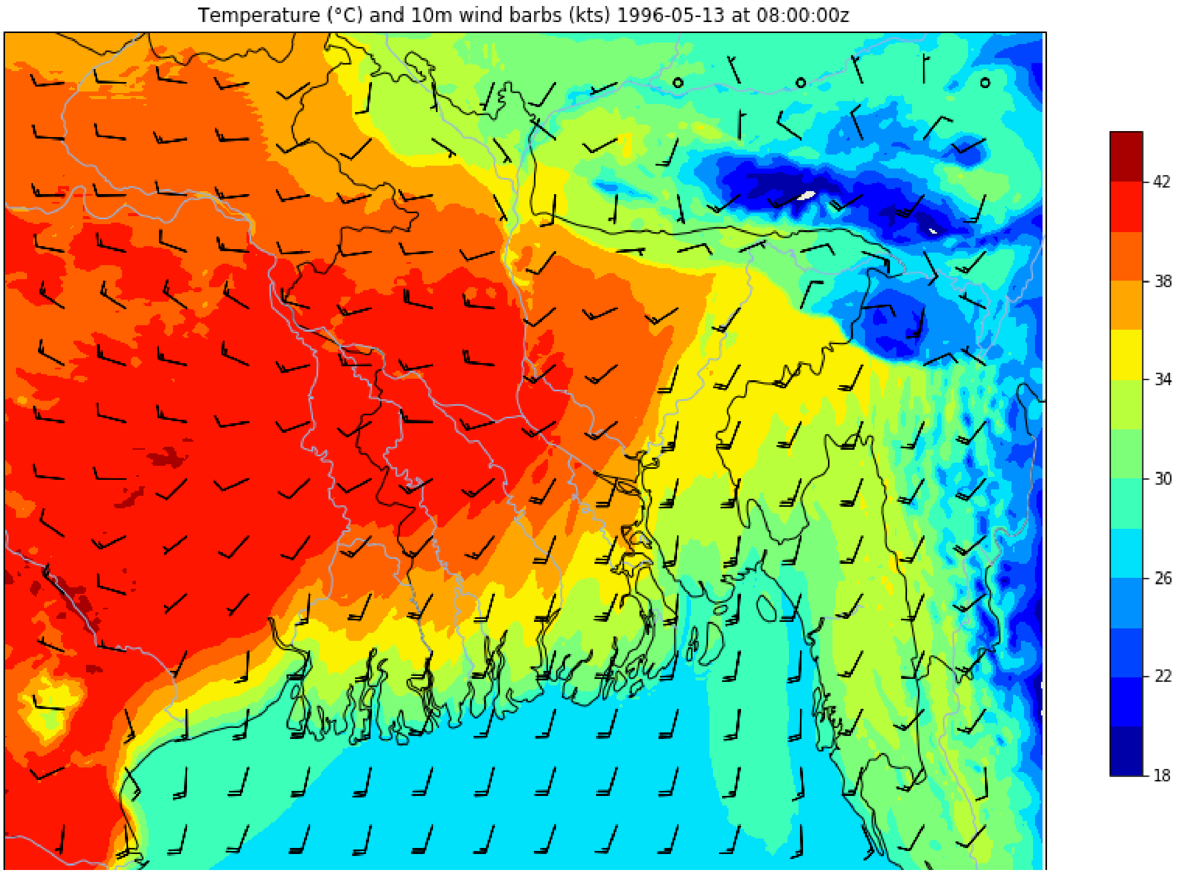

Figure 8. Air temperature (°C, color fill), and 10-m wind (knots, barbs) over Bangladesh for 0800 UTC 13 May 1996.

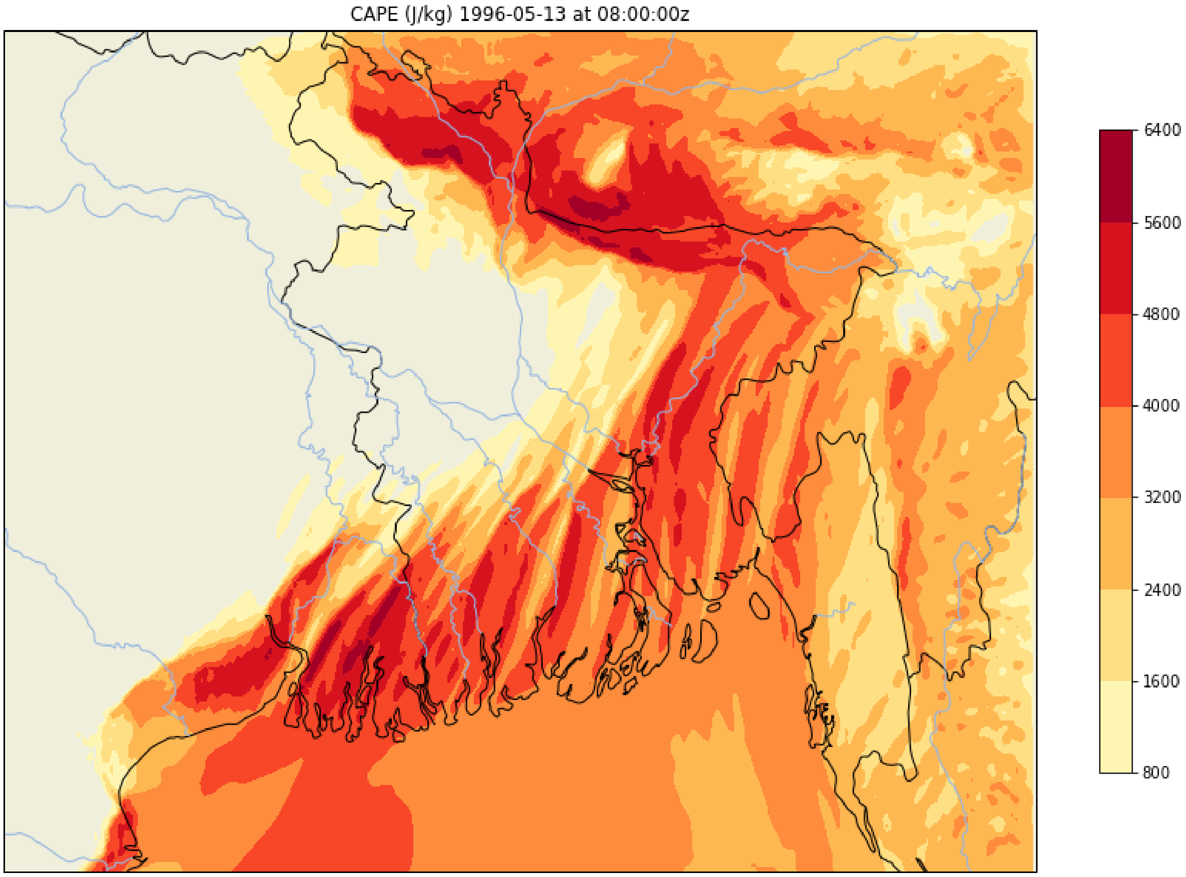

Figure 9. Surface-based CAPE (J kg^{-1}, color fill) over Bangladesh for 0800 UTC 13 May 1996.

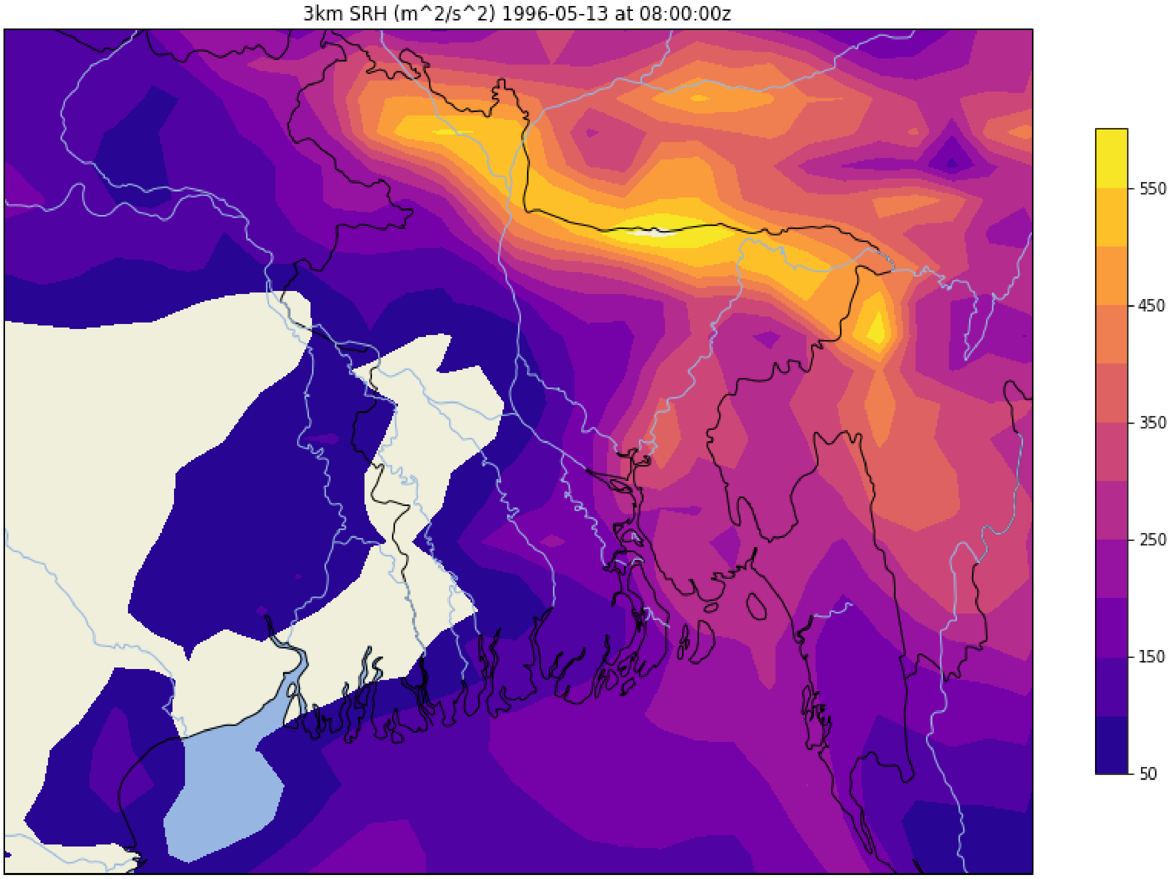

Figure 10. 3-km SRH ($m^2\ s^{-2}$, color fill) over Bangladesh for 0800 UTC 13 May 1996.

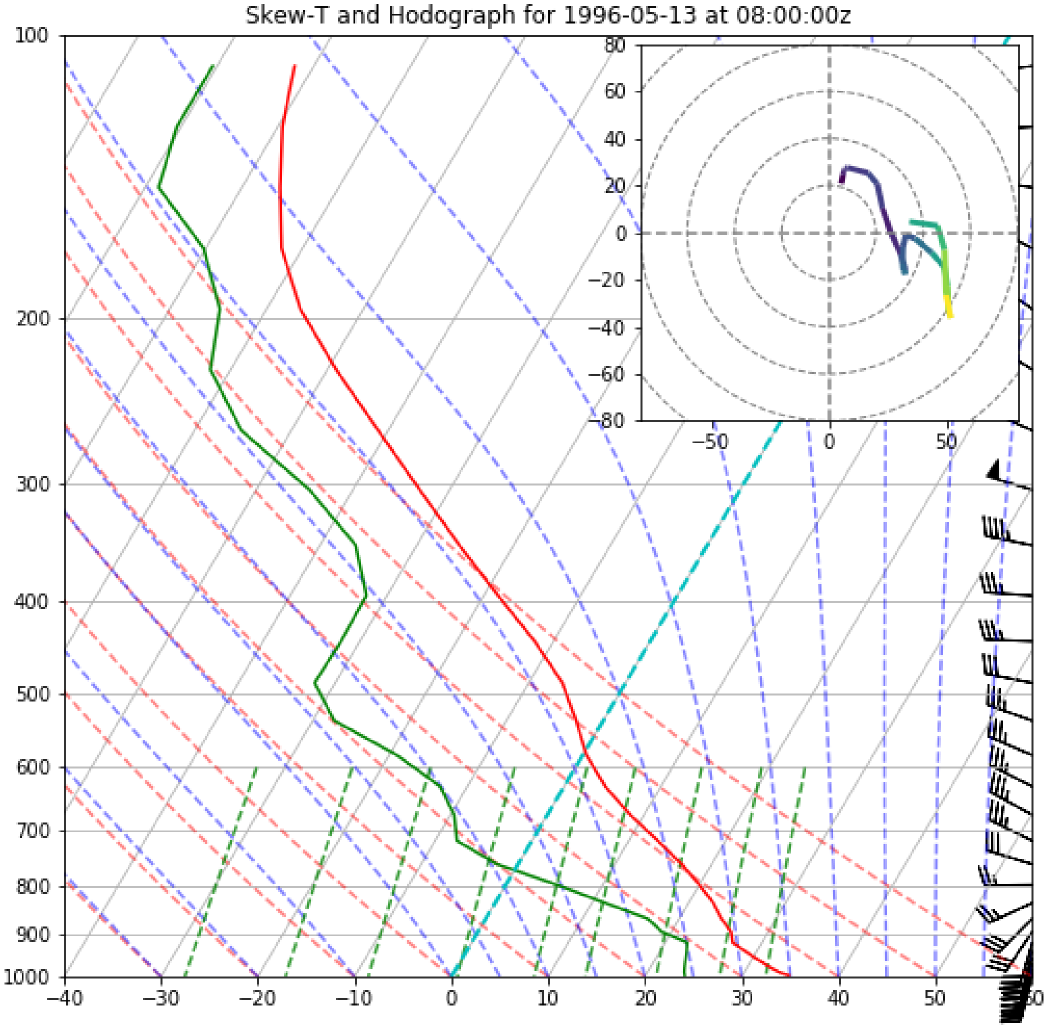

Figure 11. Skew-T diagram with inset hodograph in the upper right for the location indicated in the Figure 10 for 0800 UTC on 13 May 1996.

Figure 12. Map of Bangladesh indicating the location of the sounding site in the red dot.

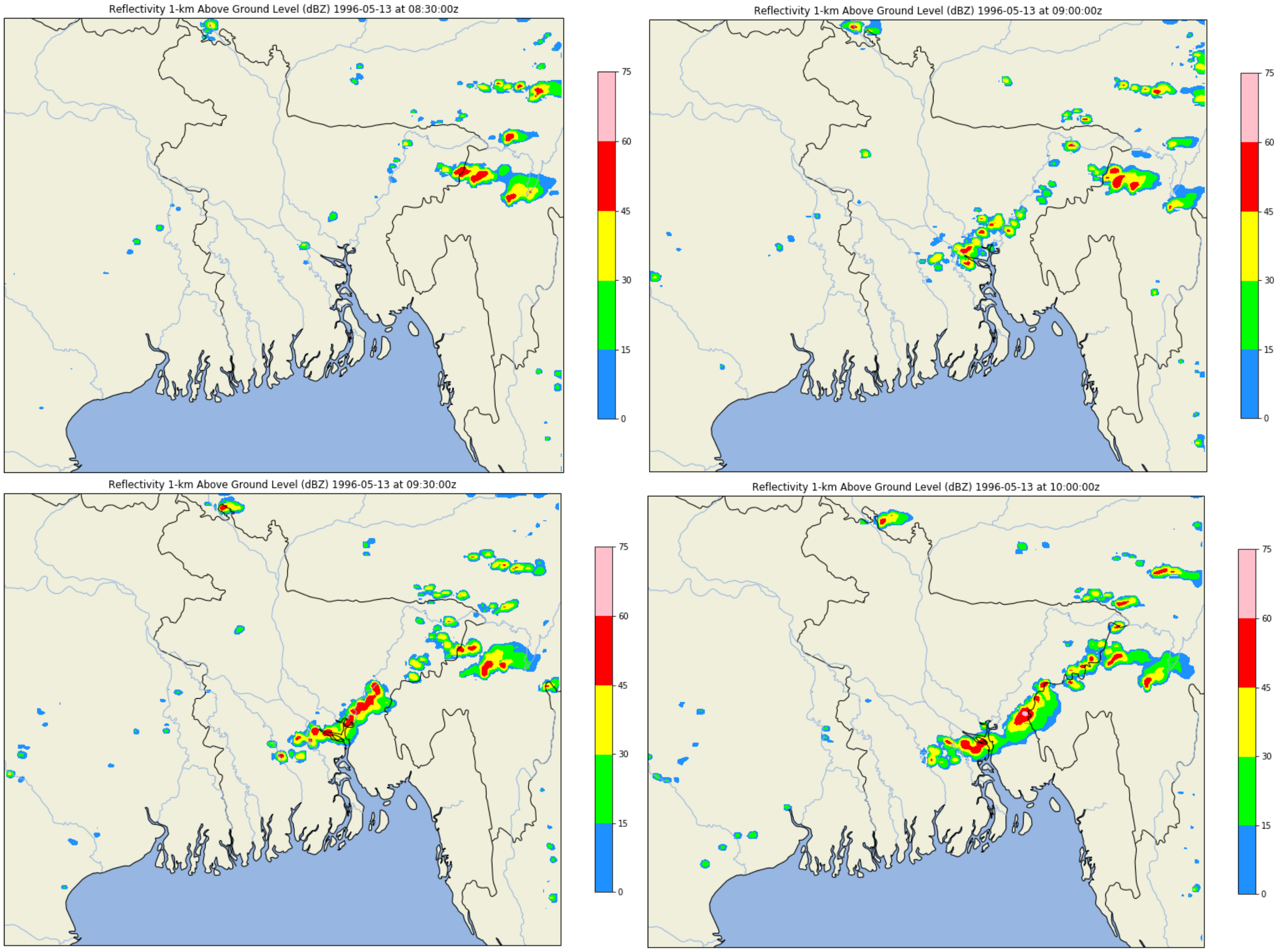

Figure 13. Simulated 1-km AGL reflectivity (dBZ) over Bangladesh for 0830 UTC in the upper left, 0900 UTC in the upper right, 0930 UTC in the lower left, and 1000 UTC in the lower right on 13 May 1996. The star represents the site of the tornado report on 13 May 1996.