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The environment associated with significant tornadoes in Bangladesh

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ABSTRACT

This paper investigates the environmental parameters favoring significant tornadoes in Bangladesh through a simulation of ten high-impact events. A climatological perspective is first presented on classifying significant tornadoes in Bangladesh, noting the challenges since reports of tornadoes are not documented in a formal manner. The statistical relationship between United States and Bangladesh tornado-related deaths suggests that significant tornadoes do occur in Bangladesh so this paper identifies the most significant tornadic events and analyzes the environmental conditions associated with these events. Given the scarcity of observational data to assess the near-storm environment in this region, high-resolution (3-km horizontal grid spacing) numerical weather prediction simulations are performed for events identified to be associated with a significant tornado. In comparison to similar events over the United States, significant tornado environments in Bangladesh are characterized by relatively high convective available potential energy, sufficient deep-layer vertical shear, and a propensity for deviant (i.e., well to the right of the mean flow) storm motion along a low-level convergence boundary.

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1. Introduction

Bangladesh experiences its severe thunderstorm season between March and May, resulting in property damage, injuries and deaths each year (Yamane et al., 2010a). During the pre-monsoon season, the ingredients for severe thunderstorms may develop including low-level moisture from the Bay of Bengal, a relatively hot and dry air mass from the Indian Subcontinent and relatively strong flow at mid- to upper-levels to provide sufficient vertical wind shear for organized convection (e.g., Petersen and Mehta, 1981; Yamane and Hayashi, 2006; Yamane et al., 2010a). These ingredients can lead to an elevated mixed layer above a moist air mass where a capping inversion suppresses convection and allows instability to build with daytime heating until localized convergence along a dryline triggers deep convection (Carlson and Ludlam, 1968). Akter and Ishikawa (2014) noted this mechanism in a case study over Bangladesh as being similar to convective initiation along the dryline in the Great Plains of North America.

Past studies have investigated tornado events across Bangladesh (Afrose et al., 1981; Ono, 1997), however as noted by Yamane et al. (2010a), the definition of tornadoes in these studies is based on arbitrary thresholds of wind speeds so that non-tornadic events may have been included in previous climatologies. The critical limitation in studying tornadoes over Bangladesh lies in the fact that the Bangladesh Meteorological Department (BMD) does not formally document tornado reports (except for a few significant events that cause extensive damage).

Yamane et al. (2010b) studied the environment of severe local convective storms which included tornadoes in addition to reports of wind, hail and lightning. Discriminating between tornadic and non-tornadic events is not generally possible if one is interested in all tornado events due to the absence of tracking tornado reports. However, by beginning with a database of tornadoes similar to Afrose et al. (1981) or Ono (1997) and only considering the most significant of these events, we will likely have a dataset associated with the most significant tornadoes. Given the dearth of formal tornado documentation, this study represents the best possible effort to follow a study similar to Cohen (2010), which was done over the U.S., in assessing the environment associated with significant tornadic storms over Bangladesh.

When assessing environmental conditions, it is important to note that the only available rawinsonde data in Bangladesh is the morning (0600 Bangladesh Standard Time) observation from Dhaka. These data are not generally representative of the environment of tornadic storms that typically occur during the afternoon and evening hours. One method of addressing the limited upper-air observational data is to use reanalysis data, numerous studies have used reanalysis data for assessing the severe thunderstorm/tornado environment (e.g. Brooks et al., 2003b; Grünwald and Brooks, 2011; Romero et al., 2007; Kaltenböck et al., 2009). Yamane

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and Hayashi (2006) utilized the European Centre for Medium-Range Weather Forecasts (ECMWFs) re-analysis (ERA-40) dataset available every 6 h on a 2.5° by 2.5° grid. As in Yamane et al. (2010b), the focus was on severe local convective storms (not solely tornadoes). However, the coarse resolution of these data precludes a suitable assessment of the near-storm environment of tornadic thunderstorms. Akter and Ishikawa (2014) examined a case study of a tornadic event in Bangladesh with 50 km horizontal resolution and 6 hourly temporal resolution reanalysis data and remarked on the need for higher temporal resolution data. Since the focus of this study is to quantify the near-storm environment of significant tornadoes, the need for high-resolution (3-dimensional) data during the afternoon and evening hours is critical. In order to provide the best possible solution given data limitations, we make use of short-term simulations using the Weather Research and Forecasting (WRF) — Advanced Research WRF (ARW) dynamical core numerical weather prediction (NWP) model (Skamarock and Klemp, 2007).

The remainder of this article is organized as follows. A climatology of probable tornadoes and associated deaths is presented in Section 2. From this initial dataset, a subset of only the most significant tornado events is considered for simulating the near-storm environment. Section 3 presents the results of ten selected numerical modeling case studies, along with a comparison to similar studies from the United States (U.S.). Conclusions are given in Section 4.

2. Climatology of significant tornadoes

2.1. Tornado database formulation

The methodology begins with the development of a comprehensive climatology of tornado reports based on past studies and historical Bangladesh media reports. Knowing that some non-tornadic events have been included in historical media reporting, only the most significant events are retained for the purposes of simulating the near-storm environment (see Section 3). Previous studies of tornado climatologies in the region (Petersen and Mehta, 1981, 1995; Afrose et al., 1981; Ono, 1997) listed tornado events according to an arbitrary definition of a tornado due to the absence of a formal tornado reporting system. The climatology compiled here is generally restricted to the area from 85° to 93°E and from 21° to 27°N (mostly Bangladesh but a portion of eastern India as well) for the period 1838–2005. The sources of information include scientific journal articles and newspaper reports. Articles were queried for only the March to May time period since that is the primary severe thunderstorm season over the Bengal region (Yamane et al., 2010a). Other sources of information include the Office of U.S. Foreign Disaster Assistance, the Centre for Research on the Epidemiology of Disasters, and the British Association for Immediate Care. The sources were scanned for information reporting on storm-related damage/fatalities that provides evidence of a tornado based loosely on Fujita (1971).

The thresholds used to determine if the event was tornadic are the following: 1) specific information such as width and path length, sharp gradients in damage or damage intensity, or description of the actual funnel or roaring sound was provided that would be indicative of a tornado, 2) heavy objects, people or animals thrown long distances, 3) flying debris such as corrugated iron sheets caused lacerations, decapitation, or loss of limbs, 4) description of catastrophic damage (e.g., entire villages reduced to rubble and/or photos showing tornadic damage), and 5) at least 15 deaths occurred inland that can be documented as unrelated to tropical cyclones. At least one of these criteria needs to be met for tornado classification. Given the lack of detailed storm surveys in Bangladesh, these types of thresholds are necessary for the development of a relatively objective tornado climatology. Unless there were at least 15 deaths, additional evidence was required to label an event as a tornado. Even if at least 15 people were killed, an event was not classified as a tornado if the documentation suggested the presence of widespread straight-line winds. High winds associated with a land-falling, tropical cyclone cannot be distinguished from the accompanying tornadoes, especially since the term cyclone was used for tropical cyclones and tornadoes. Therefore, tornadoes associated with land falling tropical cyclones were excluded altogether.

Since the housing structure is predominantly frail in Bangladesh, people are often killed by straight-line winds. For example, collapsing of roofs and capsizing of ships have been responsible for many deaths at times. In addition, weaker tornadoes are often indistinguishable from straight-line wind events since documentation for such events is extremely limited. Newspapers tend to ignore events that are less than catastrophic. Since it is very difficult to differentiate less than catastrophic tornadoes from straight-line winds, this climatology focuses primarily on the deadliest and most catastrophic events that tend to be associated with significant and violent tornadoes.

The unique aspect of this tornado climatology compared with past studies in the region (Petersen and Mehta, 1981, 1995; Afrose et al., 1981; Ono, 1997) is the blending of scientific articles, reports from the BMD, multiple newspapers and other sources over a long time period (1838–2005) as listed in Appendix A. Petersen and Mehta (1981) used scientific journals and BMD reports from 1838 to 1978. Ono (1997) used one newspaper source between 1990 and 1994. Afrose et al. (1981) considered tornado and nor'wester events between 1975 and 1979. Utilizing a blend of multiple sources to collect tornado reports has been employed in similar studies of tornadoes over Europe (e.g., Gayá, 2011; Brazdil et al., 2012; Taszarek and Kolendowicz, 2013; Simeonov et al., 2013). In addition, at least one of five criteria was used to determine if the event was tornadic (note Appendix A lists the criteria met with numerous events associated with multiple criteria).

The analysis yielded 84 tornado events from 1838 to 2005, with details for each tornado listed in Table A1 of Appendix A. Most of the events (81) denoted the number of deaths. A summary of the tornado climatology is shown via the location with the number of deaths by category (Fig. 1). The data were binned into 10-day periods to illustrate the time period during the pre-monsoon season when tornadoes tend to occur most frequently (Fig. 2). The maximum occurs in mid-April (specifically April 11–20) which agrees with the peak of severe local storms from Yamane et al. (2010a). This climatology serves as a foundation for the dataset on significant tornadoes in Bangladesh, which is the primary focus of this study. Although some tornado events are undoubtedly missed in this climatology, it is highly unlikely that a significant tornado event is missed because of the high population density.

2.2. Determination of threshold for significant tornado events

The number of deaths by event from the Bangladesh tornado climatology is shown as a cumulative distribution function in Fig. 3. In order to determine the most significant events to retain for the numerical simulations, we compare the distribution of deaths to tornado-related deaths in the U.S. where reporting of tornadoes and tornado-related deaths is much more comprehensive than Bangladesh. The dataset used for analysis is the number of tornado-related deaths in the U.S. from 1950 to 2013. There is a strong relationship between the damage rating and number of deaths. For example, all events with greater than 20 tornado related deaths were caused by a tornado associated with a damage rating of (E)F-3 or greater. Table 1 shows the percentage of U.S. killer tornado events by damage scale and further categorized for events with 10 and 20 or more tornado-related deaths. These results indicate that events with relatively large numbers of deaths are associated with tornadoes at the higher end of the E(F) damage scale. For the category of tornado events with 20 or more tornado related deaths, 92.8% of these events were associated with violent tornadoes (i.e., a damage rating of E(F) 4 or 5). Using a similar period of record, Ashley (2007) found that tornadoes with a damage rating of (E)F-4 or 5 were responsible for 67.5% of all tornado deaths in the U.S., despite accounting for only 2.1% of all tornadoes.

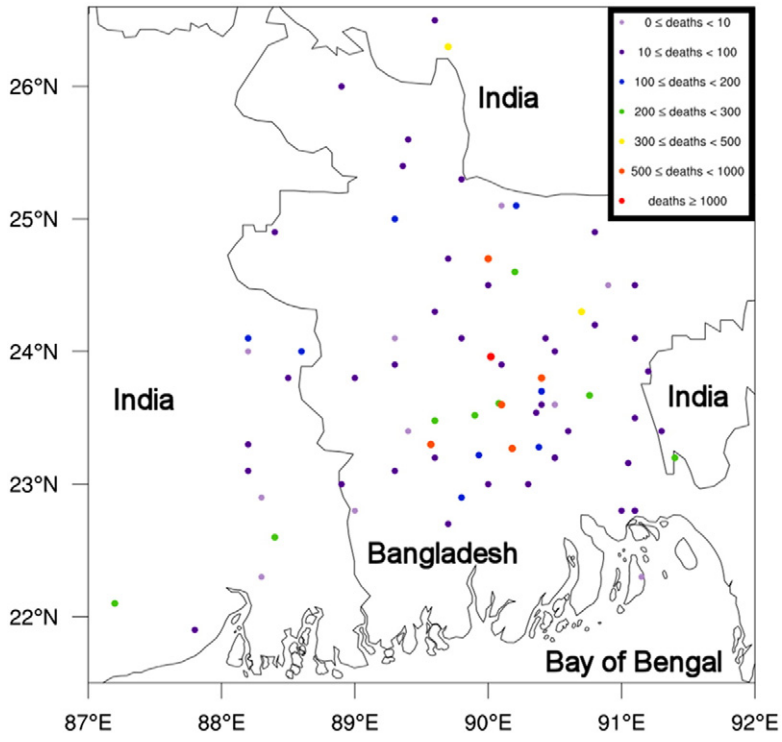

Fig. 1. Location of tornado related deaths (as defined in Section 2) over Bangladesh and eastern India from 1838 to 2005. Number of tornado related deaths colored by range given in the upper right.

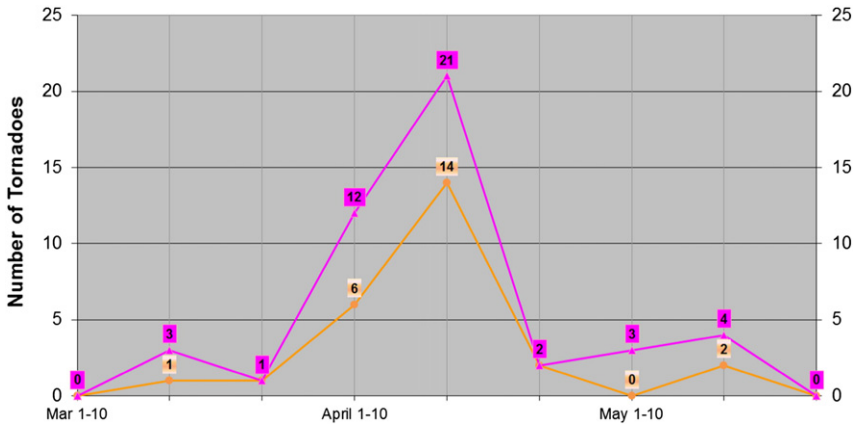

Fig. 2. Frequency of tornadoes in Bangladesh and east India between 1838 and 2005 grouped in 10 day periods between March and May with 30 (magenta line) and 100 (orange line) or more fatalities.

Although the number of tornado deaths in Bangladesh is considerably higher than the U.S., we can assess the distribution of the number of deaths to quantify the similarities between the Bangladesh dataset and the more reliable U.S. dataset. Brooks and Doswell (2001) showed that the distribution of tornadoes by (E)F-scale for the U.S. compared with several other countries[1] is similar for (E)F-3 and higher intensity events. The Weibull distribution has been shown to model observed tornado intensities (Dotzek et al., 2003) as well as path length and width (Brooks, 2003a). The objective here is to model tornado related deaths from the U.S. dataset using a similar approach to Brooks (2003a), then compare the results to a modeled distribution of deaths in our Bangladesh climatology dataset, in order to isolate the high-end events for simulating the near-storm environment.

[1] Did not include Bangladesh since damage intensity is not reported.

Since damage intensity is not recorded officially for Bangladesh, a Weibull distribution is fit to the complete record of Bangladesh tornado deaths in our climatology. The probability distribution function for the Weibull distribution is:

$$f(x) = \left(\frac{\alpha}{\beta}\right)\left(\frac{x}{\beta}\right)^{\alpha-1} \exp\left[-\left(\frac{x}{\beta}\right)^{\alpha}\right] \quad (1)$$

where α denotes the shape parameter, β is a scaling factor and x, α, and β are positive. Values of α and β are estimated with a maximum likelihood technique. For the Bangladesh dataset, the estimated $\alpha = 0.596$ and $\beta = 75.555$ for $N = 81$ cases. A cumulative distribution function that depicts the observation points along with the Weibull distribution is given in Fig. 3. A graphical technique to assess the goodness of fit of the observed data to the modeled Weibull distribution is the quantile–

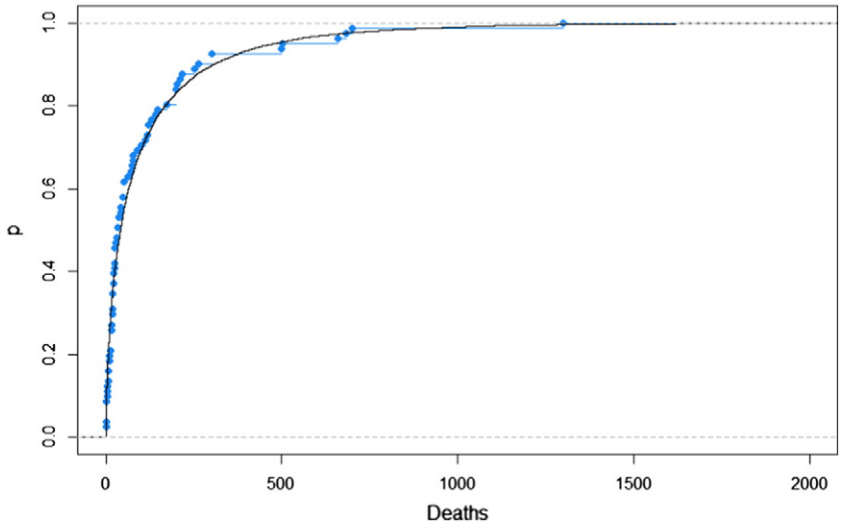

Fig. 3. Cumulative distribution function of the number of deaths for 81 tornado events identified in Bangladesh (blue dots). Black line represents a Weibull distribution fit with $\alpha = 0.596$ and $\beta = 75.555$. Cumulative probability (p) for number of deaths is shown on the ordinate.

quantile plot (Fig. 4). On the low end of the scale, the modeled distribution underestimates the empirical (observed) distribution since the points are above the diagonal (perfect-fit) line. However, as the modeled tornado deaths exceed ~15, the fit is quite good, with a slight overestimate of the modeled distribution until reaching large values (~1000). Since we are most interested in the middle to high end events (to isolate significant tornadoes), the underestimation at lower values is inconsequential. Given the uncertainty of using deaths as a proxy for tornado reporting in Bangladesh, the modeled Weibull distribution provides the best possible alternative to analyzing significant tornadoes in Bangladesh, as long as we are not concerned with low-end tornadoes.

We then perform a Weibull distribution fit to the U.S. dataset of violent tornadoes ((E)F4 or (E)F5) using the data from 1950 to 2013, resulting in a parameter fit of $\alpha = 0.488$ and $\beta = 2.737$ for $N = 784$ cases. A comparison of the distributions of U.S. violent tornado deaths to tornado-related deaths in Bangladesh is shown in Fig. 5. The distributions represent the probability of the number of tornado related deaths given that a tornado occurs (for Bangladesh), while for the U.S. dataset it is given that a tornado of F4 or greater intensity occurs. There are considerably more tornado related deaths in Bangladesh than in the U.S. (the population density in Bangladesh for 2011 was 1174/km^2, while in the U.S. it was approximately 35/km^2). Other factors leading to higher number of deaths are much poorer building construction compared to the U.S. and also the lack of a warning system. If the distribution of tornado related deaths is similar between both countries we can retain only the top 50% of tornado events and have confidence that they are associated with significant tornadoes. Recall that the tornado events chosen for Bangladesh already filtered out the majority of weaker events by the criteria described in Section 2. This method provides tornado events that would likely have been rated towards the higher end of the F scale, if damage ratings existed. Since the majority of tornado related deaths in the U.S. are caused by violent tornadoes, we are confident that the majority of tornado-related deaths in the Bangladesh climatology are represented by the most significant/violent tornadoes as well. The top 50% of tornado events in Bangladesh correspond to $p = 0.5$ in Fig. 5, or a value of ~40 or more deaths per event. Therefore, we utilize 40 deaths as a proxy threshold for the most significant tornadoes in order to simulate the near-storm environment.

Table 1
Percentage of tornado events at the specified (E)F damage scale in the case of 10 and 20 or more tornado related deaths for the U.S. from 1950 to 2013.

E(F) damage scale	% of events with 10 or more deaths (N = 151)	% of events with 20 or more deaths (N = 69)
F0	0	0
F1	0.7	0
F2	0	0
F3	13.2	7.2
F4	56.3	46.4
F5	29.8	46.4

3. Assessment of the near-storm environment with numerical simulations

In addition to the 40-death proxy criterion, simulation case selection is also based on the availability of ECMWF ERA-Interim Global Reanalysis data (Dee and Coauthors, 2011), which spans 1989–2008. This dataset was chosen for initial and boundary conditions to drive the ARW NWP model simulations because of its relatively high horizontal resolution (0.7° grid spacing) relative to some other re-analysis products, thereby offering the best step-down ratio of grid resolution based on the desired scales to be modeled (i.e., ranging from synoptic to convection-allowing). The use of synoptic-scale re-analysis data to initialize NWP model simulations has been found to be sufficient to capture processes that play a major role in tornado outbreaks (Shafer et al., 2009). Nine events meet the 40+ death criterion between 1989 and 2008. One recent case with fewer than 40 deaths is added (30 deaths on 4 May 2003) due to overwhelming evidence of substantial tornado damage (BBC news reporting this as a tornado that had "flattened" the whole village of Noabadi; also, reports of many of the injured having lost hands or feet from flying debris). This resulted in 10 total cases to be studied with numerical simulations as summarized in Table A1. Despite the relatively small sample size, this process provides strong confidence that these events are associated with significant tornadoes, in order to capture the environment associated with such events.

The ARW NWP model is configured to use nonhydrostatic dynamics on a one-way triple nested domain (Fig. 6). Table 2 summarizes the ARW model configuration and physics parameterizations used in the simulations, which omits the use of cumulus parameterization on the innermost grid to enable convection-allowing details to develop on the 3-km nested grid (Kain et al., 2010). Twelve-hour simulations are performed for each case with the ARW model initialized at 0000 UTC with an end time of 1200 UTC. Output from the 3-km domain (available

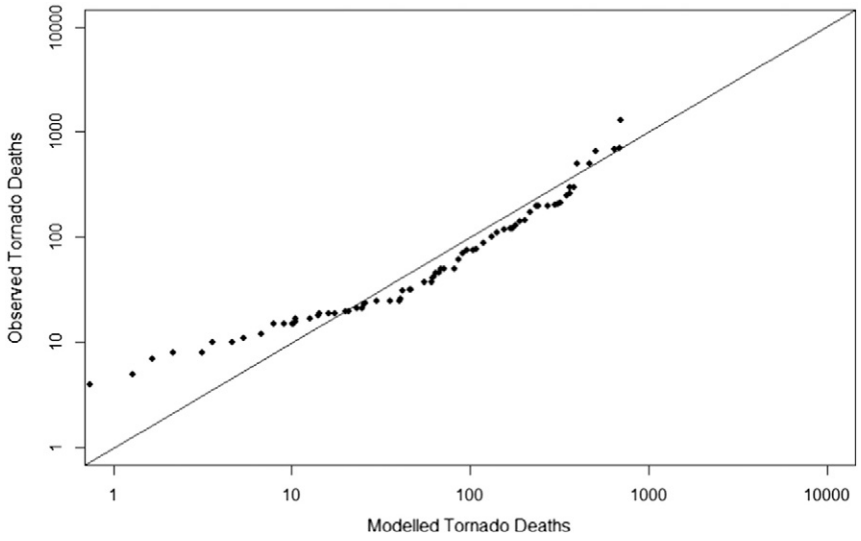

Fig. 4. Quantile–quantile plot for Weibull distribution fit to tornado-related deaths in Bangladesh. Axes are plotted on a logarithmic scale.

every 30 min) is analyzed to assess the near-storm environment and to verify that model forecast convection early in the day did not contaminate the warm sector where the tornado occurred later in the day. In nine of the ten cases, the convection-allowing 3-km model grid correctly simulated the occurrence of afternoon/evening convection in the vicinity of the observed tornado, although not necessarily at the correct time and location given typical NWP model uncertainty. The one remaining case that did not simulate convection near the tornado report by 1200 UTC is still included because the warm sector conditions were comparable to surface observations (not shown).

Proximity soundings were derived from the nearest-neighbor grid point to the observed tornado location 1 h prior to the simulated initiation of the afternoon/evening deep, moist convection. This is relatively close in spatial and temporal proximity to the tornado event compared to other studies (Potvin et al., 2010), however each simulated event was analyzed for convective feedback (e.g. simulated convection in a region where no convection was observed). The relatively close proximity and absence of convective feedback concerns increased confidence in the representativeness of the simulations. One noteworthy feature that appeared in many simulations is the presence of an early-day mesoscale convective system (MCS) originating from the Cherrapunji region (northeast of Bangladesh). These MCSs often produce an outflow boundary that interacts with an eastward-propagating dryline during the afternoon/evening hours, leading to convective initiation over Bangladesh or eastern India. Visible satellite imagery of a subset of these events (not shown) confirms this phenomenon to be a common occurrence among the significant tornado events examined. Careful attention is given to ensure the afternoon/evening simulated convection occurred on the warm side of MCS outflow boundaries originating from the Cherrapunji region.

From these model proximity soundings, a composite sounding is calculated (Fig. 7) which provides a summary of the "average" environment for the cases highlighted in Table A1. The composite sounding exhibits abundant low-level moisture, relatively dry air aloft (providing steep mid-level lapse rates) and sufficient deep-layer vertical shear. These ingredients were identified in the Introduction section as being important factors for severe thunderstorm development, however, a more detailed analysis is needed, beyond just the "average" environment. From the model proximity soundings, various severe weather parameters are calculated, similar to past studies that used observed or

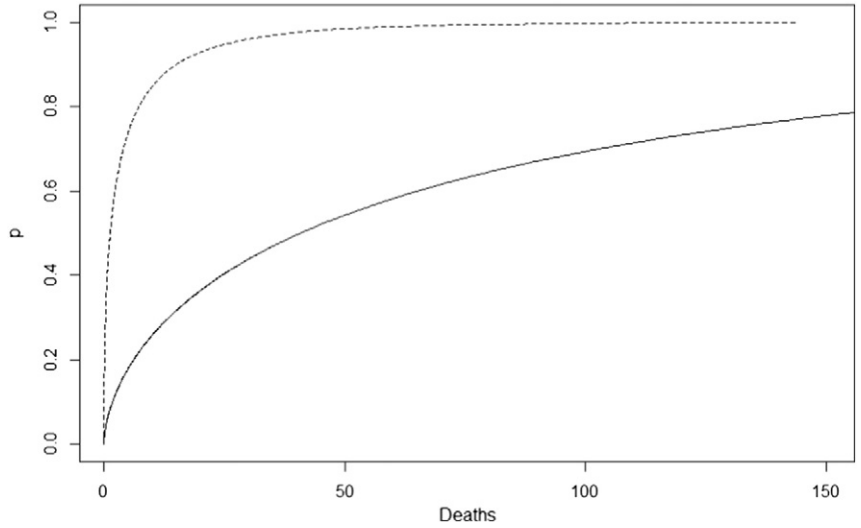

Fig. 5. Cumulative distribution function of number of tornado related deaths in Bangladesh (solid line) and for those in the U.S. from 1950 to 2013 for F4 or greater tornadoes (dashed line). Cumulative probability (p) for number of deaths is shown on the ordinate.

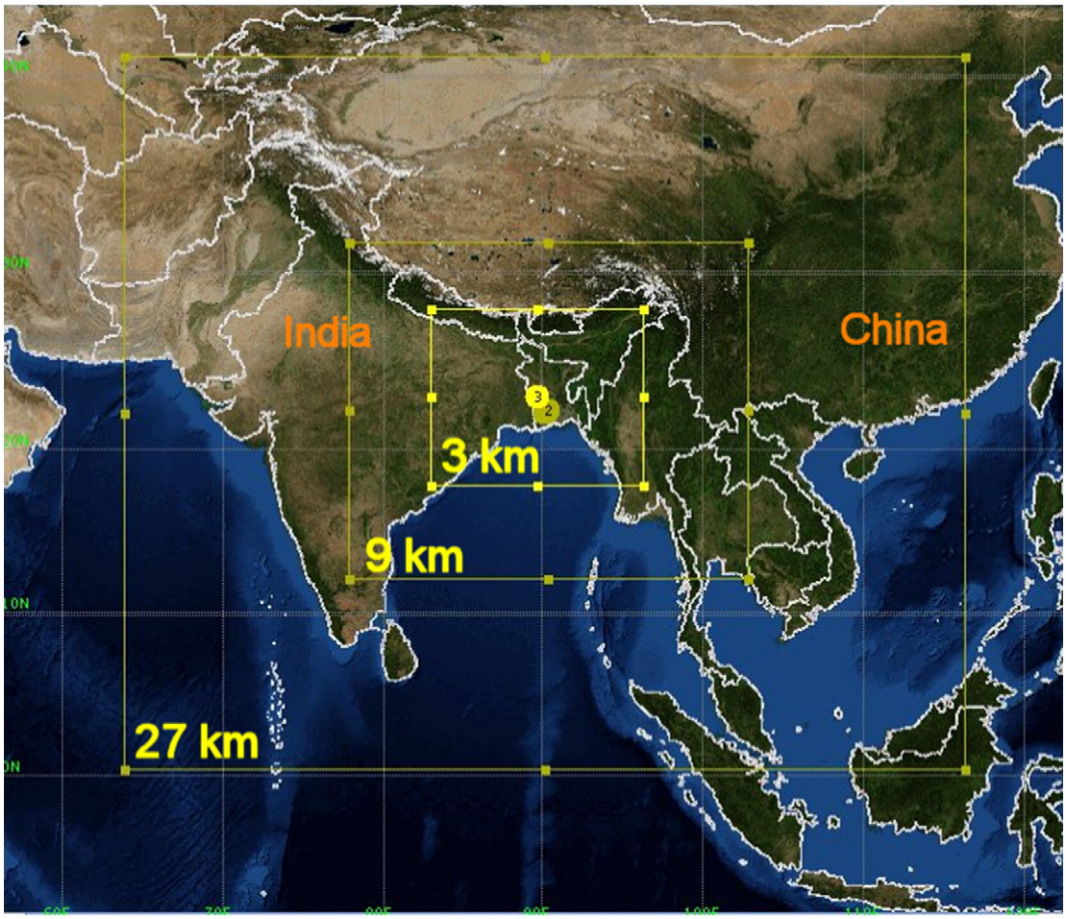

Fig. 6. Nested domain configuration utilized for the ARW simulations. Horizontal grid spacing of each nested domain is listed in the lower left corner. Bangladesh lies at the center of the innermost domain.

model soundings (Rasmussen and Blanchard, 1998; Thompson et al., 2003; Craven and Brooks, 2004; Cohen, 2010). Fig. 8 shows the distribution of most unstable and mixed-layer convective available potential energy (MUCAPE and MLCAPE) for the ten simulated cases. A comparison with values from U.S. studies indicate that Bangladesh CAPE values are overall much higher than in U.S. significant tornadoes (EF2 or greater). Median values of MLCAPE for the cases highlighted in Table A1 are 48% (Cohen, 2010) and 43% (Thompson et al., 2003 sigtor category) greater than studies over the U.S. CAPE values are also considerably higher than those found in European significant tornadoes (Romero et al., 2007; Graf et al., 2011). Given the large discrepancy in CAPE values between Bangladesh and U.S. tornado events, we may question if mid-level lapse rates are comparable; however, the results in Fig. 9 confirm that Bangladesh mid-level lapse rates (median ~6.4 °C km^{-1}) are comparable to significant tornado events in the U.S. (Lane, 2008; with a median value near 6 °C km^{-1}).

Table 2
ARW model grid configuration and physics parameterization choices used for the near-storm environment simulations.

Dynamics	Non-hydrostatic
Horizontal grid spacing	27, 9 and 3 km (1-way nesting)
Horizontal grid system	Arakawa C-grid staggering
Vertical coordinate	Terrain following sigma-pressure (60 levels)
Radiation parameterization	Rapid radiative transfer model (RRTMG)
PBL parameterization	Mellor–Yamada–Janjic
Land surface	Noah land surface model
Cumulus parameterization	Betts–Miller–Janjic for 27-km grid, none for others
Microphysics	Lin et al. (1983) 5-class single moment scheme

There are two likely reasons that support higher CAPE values over Bangladesh. First, average sea surface temperature (SST) over the adjacent Bay of Bengal in April and May is ~29.5 °C (Jaswal et al., 2012), while the average value over the same time period for the Gulf of Mexico is 25.5 °C.[2] The warmer SST in the Bay of Bengal provides higher surface dewpoint temperatures compared to those observed in the U.S. (with the moisture source from the Gulf of Mexico), which can also lead to higher 0–3 km CAPE. The importance of 0–3 km CAPE was introduced by Rasmussen (2003), with an analysis of this parameter shown in Fig. 10. The median value is 227 J kg^{-1}, compared with 64 J kg^{-1} from Rasmussen (2003) and 110 J kg^{-1} from Lane (2008). The second factor that likely contributes to higher CAPE in Bangladesh is the equilibrium level (Fig. 11). Since Bangladesh is at a lower latitude than the U.S., its tropopause heights (and thus equilibrium levels) are typically much higher, leading to a larger area of positive buoyancy at upper-levels relative to typical mid-latitude convection over the U.S.

Another favorable factor for tornadoes is a relatively low Lifting Condensation Level (LCL; Rasmussen and Blanchard, 1998). The median LCL values in the Bangladesh cases (Fig. 12) are slightly higher (1083 versus 1004 m AGL) and span a greater range than the significant tornado category presented in Thompson et al. (2003), and higher than 945 m, from Taszarek and Kolendowicz (2013) for F2/F3 tornadoes over Poland. This is most likely due to the inclusion of cool season events

[2] NOAA Physical Oceanography Division (PHOD) of AOML (Atlantic Oceanographic and Meteorological Laboratory).

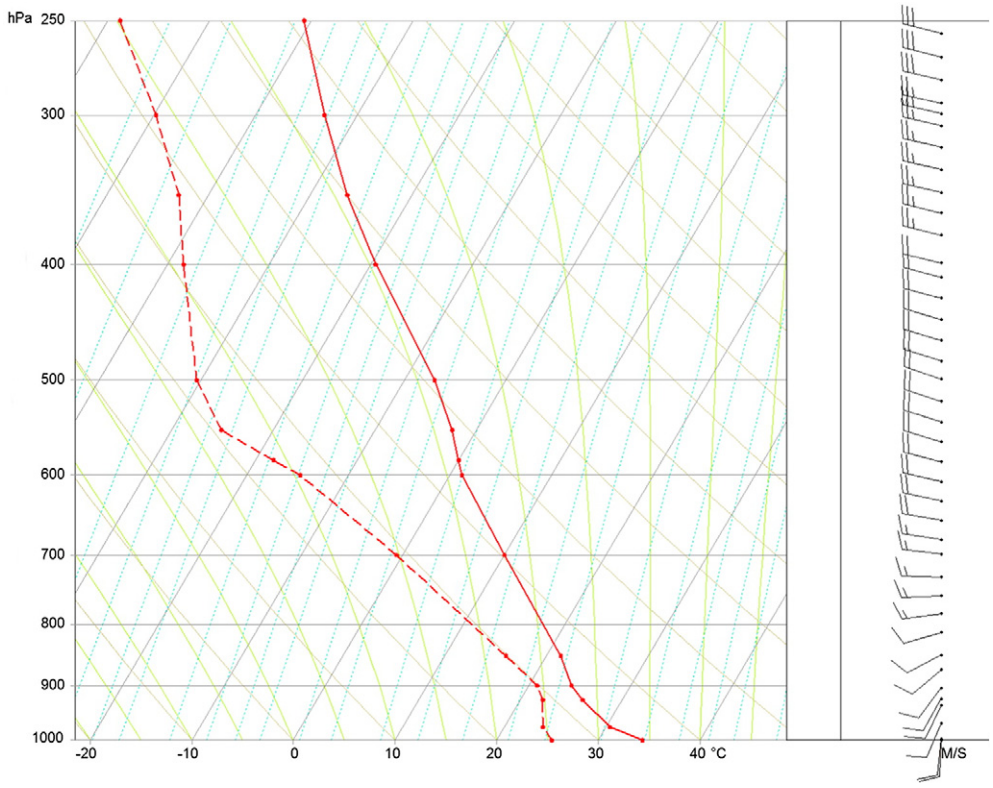

Fig. 7. Composite sounding calculated from the ARW proximity soundings for the highlighted cases shown in Table A1. MUCAPE = 5606 J kg^{-1}, LCL = 1140 m AGL, 0–3 km AGL MUCAPE = 330 J kg^{-1}, 0–3 km bulk shear magnitude = 19 m s^{-1}.

over the U.S. and Europe, while in Bangladesh there are no cool season events due to their low latitude. CIN values were also computed, however with proximity soundings so close in space and time to model forecast convective initiation, MUCIN values were zero in eight of the ten cases, while MLCIN values were zero in six of ten cases (not shown).

Shear parameters are also calculated from the simulations shown highlighted in Table A1 (Fig. 13). Deep-layer shear values were slightly less than those found in studies over the U.S. (e.g., Thompson et al., 2003; Rasmussen and Blanchard, 1998; Lane, 2008) and Poland (e.g., Taszarek and Kolendowicz, 2013); however, the low-level shear values were even less. The median 0–1 km shear is 7.5 m s^{-1}, less than U.S. significant tornado environments (10.4 m s^{-1} in Thompson et al., 2003, 17 m s^{-1} in Cohen, 2010) and 10.2 m s^{-1} over Poland (in Taszarek and Kolendowicz, 2013) for F2/F3 tornadoes. Storm-relative helicity (Fig. 14) and storm-motion from the Bunkers et al. (2000) method (not shown) are also generally lower than those found over the U.S. and Europe, where winds aloft are typically stronger due to

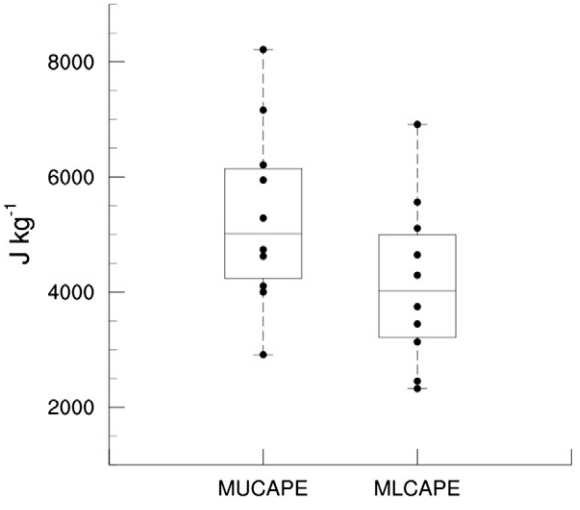

Fig. 8. Box and whisker plots of most unstable (MU) and lowest 100 hPa mixed layer (ML) convective available potential energy (CAPE) from the ARW simulations for the events highlighted in Table A1. Boxes denote the 25th to 75th percentiles, with horizontal bar at the median value. Dashed vertical lines (whiskers) extend to the minimum and maximum values. Individual data points are indicated by black dots.

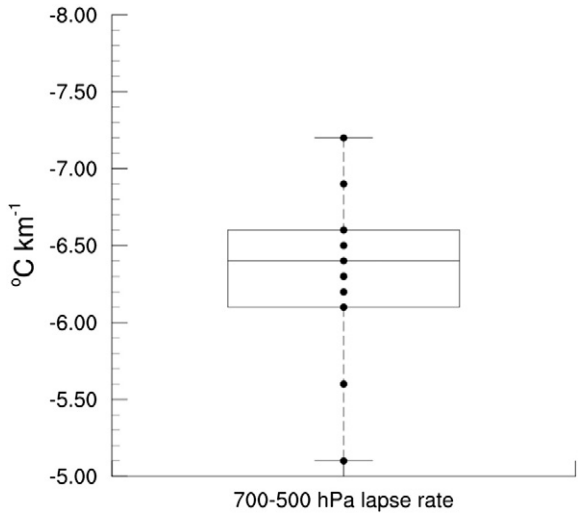

Fig. 9. Box and whisker plots of 700–500 hPa lapse rates (°C km^{-1}) from the ARW simulations for the events highlighted in Table A1. Boxes denote the 25th to 75th percentiles, with horizontal bar at the median value. Dashed vertical lines (whiskers) extend to the minimum and maximum values. Individual data points are indicated by black dots.

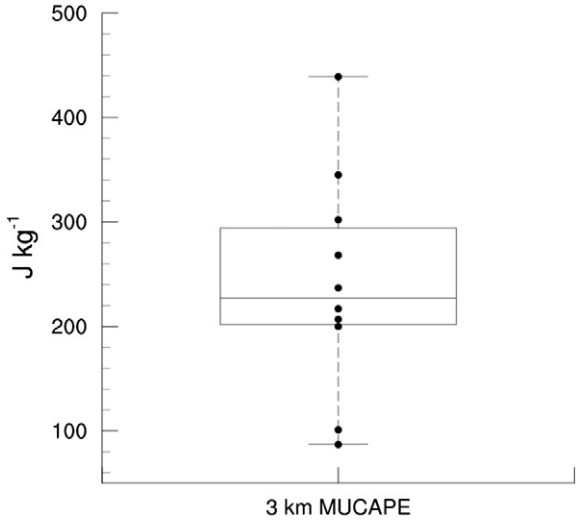

Fig. 10. As in Fig. 8 except MUCAPE in the lowest 3 km AGL.

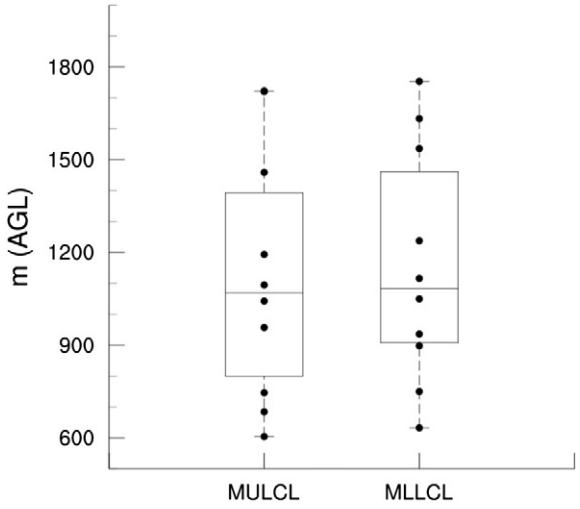

Fig. 12. Box and whisker plots of most unstable (MU) and lowest 100 hPa mixed layer (ML) LCL height (m AGL) from the ARW simulations for the events highlighted in Table A1. Boxes denote the 25th to 75th percentiles, with horizontal bar at the median value. Dashed vertical lines (whiskers) extend to the minimum and maximum values. Individual data points are indicated by black dots.

the higher latitude and closer proximity to the jet stream. With generally weaker flow aloft, storm-relative motion is that much more important to enhance low-level helicity, which can be accomplished when convection develops and/or interacts with MCS outflow boundaries from the Cherrapunji region. Ferdousi et al. (2015) show that the maximum thunderstorm frequency during the pre-monsoon season occurs over northeast Bangladesh, accounting for the relatively high frequency of MCS outflow boundaries there.

An example of convection interacting with a pre-existing outflow boundary can be seen in visible satellite imagery for the 13 May 1996 case (Fig. 15). At 0600 and 0700 UTC the imagery shows an outflow boundary oriented along and southeast of a reference marker (where later convective initiation occurred), while the MCS that produced the outflow boundary can be seen southeast of the reference marker. Convective initiation occurred near 0800 UTC at the intersection of the outflow boundary and dryline (depicted below in Fig. 16). Initial storm movement was east-southeast, but then changed to almost due south (350°) as can be seen on the 1100 UTC image relative to the reference marker in Fig. 15. The storm motion calculated from Bunkers method was 310° at 13 m s^{-1}. Table 3 illustrates the variations of SRH and 300 hPa SR (storm-relative) wind speed using different storm motion directions. The observed storm motion direction is taken from newspaper accounts of damage and the survey of Schmidlin and Ono (1996). In this example, there was a 16(40) % increase to the 0–1(0–3) km SRH respectively and a 33% increase in the 300 hPa SR wind speed. The ARW simulation for this event (Fig. 16) shows the MCS outflow boundary produced by morning convection followed by afternoon simulated convection along the dryline and outflow boundary. The most intense simulated convection occurs along the intersection of the dryline and outflow boundary. Although there is more convection along the dryline being simulated than observed, the successful forecast of an MCS

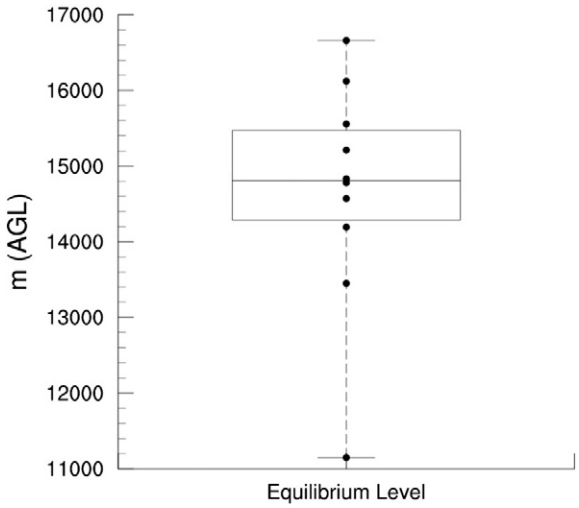

Fig. 11. Box and whisker plots of equilibrium level (m AGL) from the ARW simulations for the events highlighted in Table A1. Boxes denote the 25th to 75th percentiles, with horizontal bar at the median value. Dashed vertical lines (whiskers) extend to the minimum and maximum values. Individual data points are indicated by black dots.

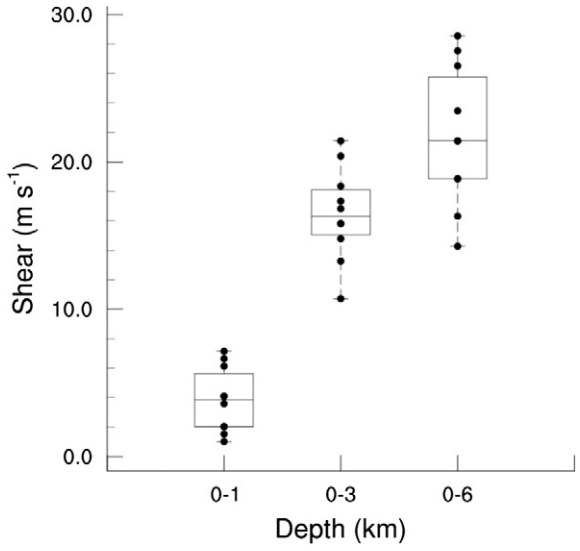

Fig. 13. Box and whisker plots of 0–1, 0–3, and 0–6 km AGL bulk shear magnitude (m s^{-1}) from the ARW simulations for the events highlighted in Table A1. Boxes denote the 25th to 75th percentiles, with horizontal bar at the median value. Dashed vertical lines (whiskers) extend to the minimum and maximum values. Individual data points are indicated by black dots.

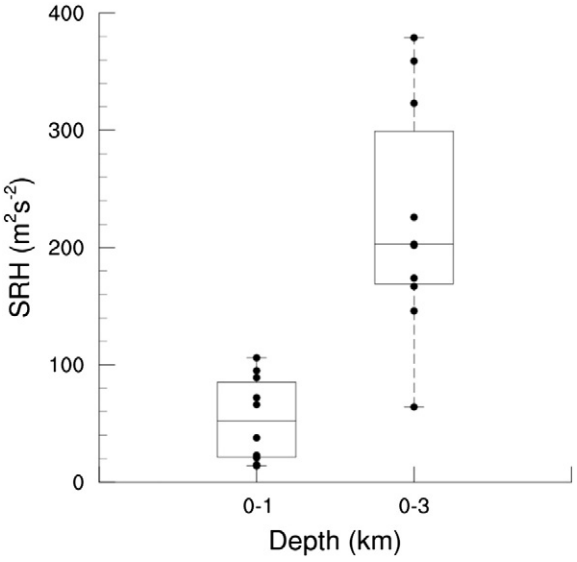

Fig. 14. Box and whisker plots of 0–1, and 0–3 km AGL storm-relative helicity (SRH, units of $m^2 s^{-2}$) from the ARW simulations for the events highlighted in Table A1. Boxes denote the 25th to 75th percentiles, with horizontal bar at the median value. Dashed vertical lines (whiskers) extend to the minimum and maximum values. Individual data points are indicated by black dots.

outflow boundary, the most intense storm being along the intersection of this boundary with the dryline and a deviant storm motion (close to observed) provides confidence in the model's ability to capture these important aspects of tornadic thunderstorms in Bangladesh.

Accounting for storm-motion in consideration of shear parameters is critical (Zeitler and Bunkers, 2005), as this may partially account for the SRH values that appear relatively low in comparison to studies done in the U.S. and Europe. Although the magnitude of the shear values is generally sufficient for supercells, the range of values on the low end suggests that the high-CAPE/weak shear environment is not uncommon. Studies over the U.S. have shown (Hodanish and Davies, 2002; Davies, 2002) that the ingredients needed for significant tornadic storms in these environments are found in the cases simulated over Bangladesh. This includes relatively large values of 0–3 km CAPE (i.e., Fig. 10; >200 J kg^{-1} over the U.S. in Davies, 2002), low values of CIN, a pre-existing convergence boundary, 300 hPa SR flow greater than 20 m s^{-1} and a storm motion that is deviant (i.e., well to the right of the mean flow). Based on the tornado climatology presented in Table A1, the frequency of deviant storm motion can be considered for 22 cases that tornado direction could be determined. In 14 (64%) cases, the tornado moved between southeast to south, which is to the right of the mean mid- to upper-level west to west-northwesterly flow during the pre-monsoon season. This predominant storm motion is likely due to a combination of propagation along a low-level convergence boundary and/or dynamical effects of a right-moving supercell. Discrete thunderstorm propagation (e.g., Newton and Fankhauser, 1964; Weaver, 1979) is not uncommon during these cases since storm-motion is generally slower (relative to the U.S. and Europe), and MCS outflow boundaries often exist in the warm sector.

4. Conclusions

The environment associated with significant tornadoes in Bangladesh was assessed through a simulation of ten recent events. Since tornadoes are not officially reported in Bangladesh, a tornado climatology dataset was created from previous publications and newspaper articles that were queried over a long period along with detailed reports showing evidence of tornadoes. From this climatology, the number of deaths is used as a proxy to discriminate significant tornadoes. Weibull distributions were fit to the number of tornado deaths for the Bangladesh dataset, and compared with a dataset for F4 or greater tornadoes over the U.S. Although the number of deaths in Bangladesh is typically much higher than in the U.S., comparisons between the distributions suggest that the more significant tornadoes are associated with the highest number of

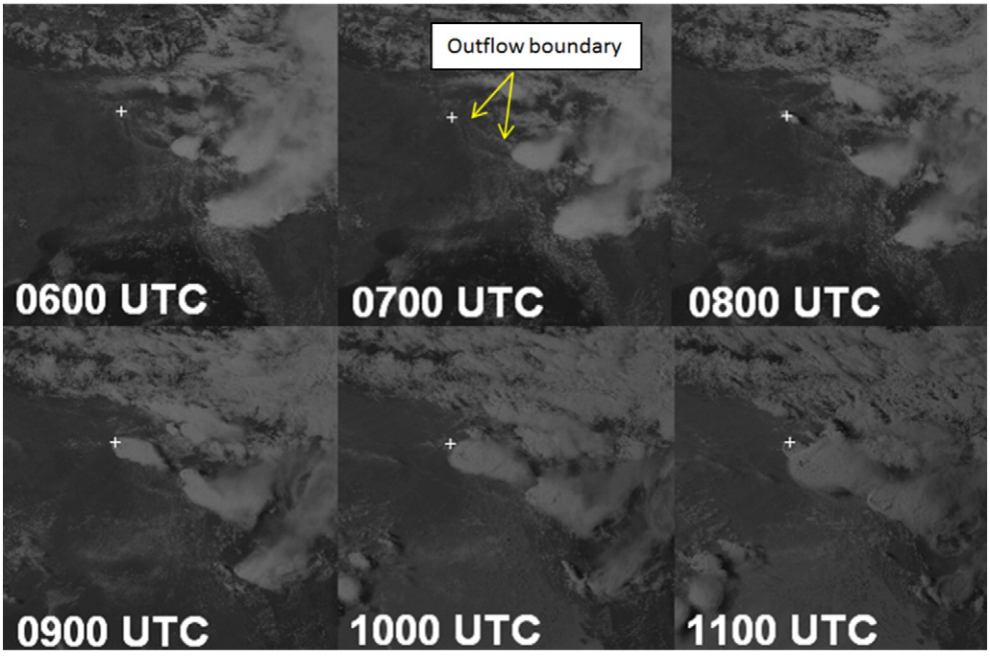

Fig. 15. Geostationary Meteorological Satellite (GMS) visible satellite imagery from 13 May 1996 centered over Bangladesh. + sign is a reference marker close to convective initiation location.

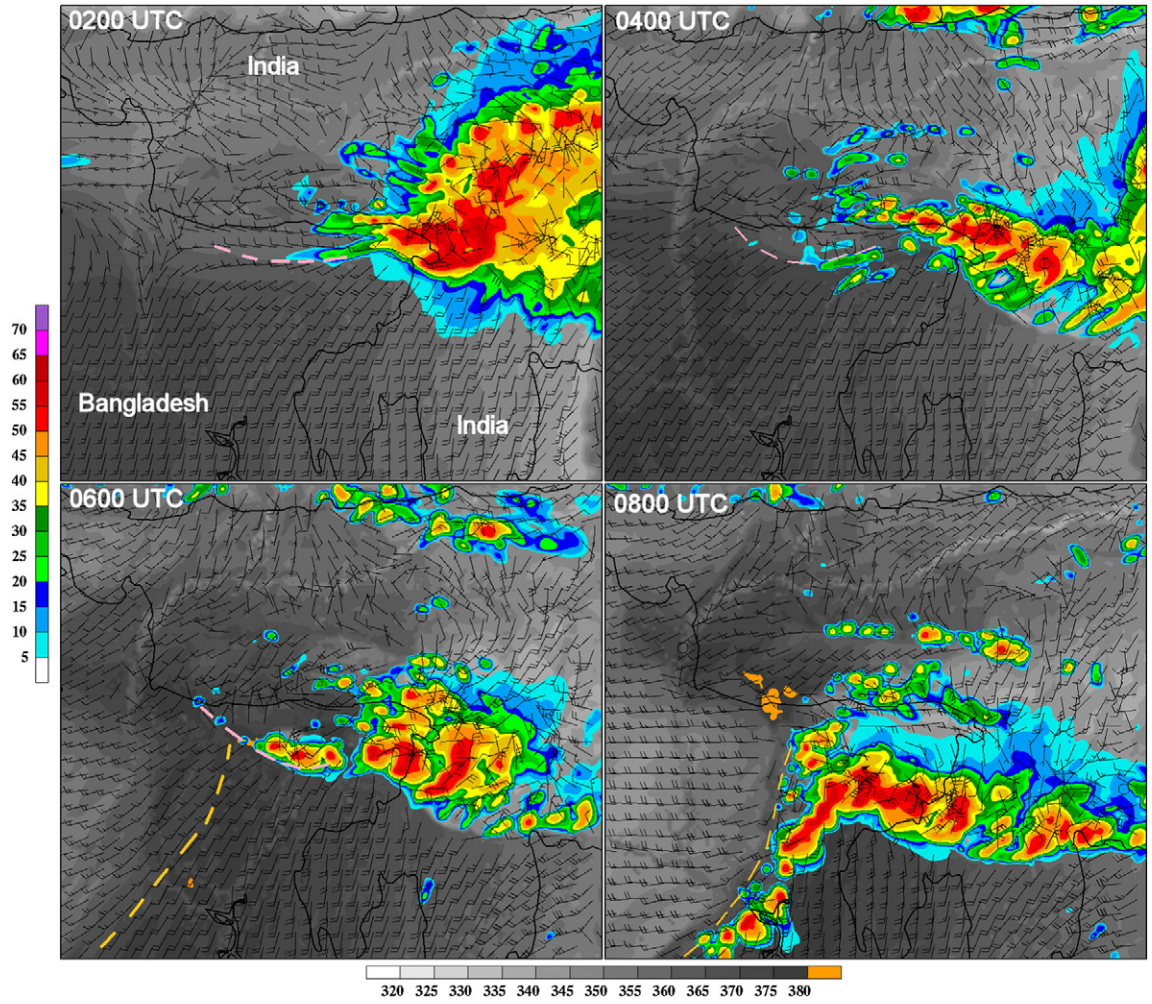

Fig. 16. ARW simulated composite reflectivity (dBZ; color shading with scale on the left), equivalent potential temperature (K; gray shading with scale on bottom) and 10-m winds (half barb = 2.5 m s^{-1}, full barb = 5 m s^{-1}). The ARW model is initialized at 0000 UTC 13 May 1996 with forecast valid times (on 13 May) labeled at the upper left of each panel. The MCS outflow boundary is depicted in dashed pink, with the dryline depicted in dashed orange/yellow.

deaths. Only the top 50% of cases for Bangladesh were considered to be significant tornadoes for the purposes of simulating the near-storm environment. Cases of primarily ~40+ deaths per event were simulated based on the availability of ECMWF ERA-Interim 0.7° resolution re-analyses, which provided relatively high resolution initial and boundary conditions for the ARW model for events between 1989 and 2008.

Proximity soundings from the numerical simulations were used to assess the conditions of the near-storm environment of significant tornado events. Results of the numerical simulations show CAPE values to be considerably higher than other regions of the world that officially report tornadoes. Specifically for significant tornadoes, median values of MLCAPE for the Bangladesh simulated cases are 48% (Cohen, 2010) and 43% (Thompson et al., 2003 sigtor category) greater than these studies over the U.S. This is likely due to high SST in the Bay of Bengal and the relatively high equilibrium levels due to high tropopause heights at the low latitude of Bangladesh (~25° N). The LCL height and mid-level lapse rate were found to be comparable to studies over the U.S. Deep-layer shear that was found to be slightly less than the previous studies over the U.S.; however, low-level (0–1 km AGL) shear was found to be considerably less compared with studies over the U.S. (Thompson et al., 2003; Cohen, 2010) and Europe (Taszarek and Kolendowicz, 2013). It is hypothesized that many events would be characterized by high CAPE and sufficient deep layer shear for supercells that exhibit discrete propagation along a low-level convergence boundary. Morning MCS activity is common over the highlands of northeastern India near Cherrapunji, thereby producing outflow boundaries that advance south-westward into the warm sector. With the typical slow storm motion, discrete propagation along a boundary may commonly occur, compensating for the lack of low-level shear diagnosed from the numerical simulations. The 13 May 1996 event was highlighted as a representative Bangladesh tornadic supercell that moved well to the right of the mean flow.

Table 3
Values of storm-relative helicity (SRH) and 300-hPa storm relative (SR) wind speed for different storm motion directions of the 13 May 1996 tornadic supercell. Storm speed utilized is from Bunkers method (13 m s^{-1}).

Storm motion direction	0–1 km SRH (m^2 s^{-2})	0–3 km SRH (m^2 s^{-2})	300 hPa SR wind speed (m s^{-1})
310 (Bunkers method)	21	174	16
330 (mean observed)	24	237	20
350 (observed later segment, after right turn along MCS boundary)	25	289	24

An important consideration when comparing significant tornado environments between Bangladesh and comparable studies in the U.S. and Europe is the fact that cool season events do not occur in Bangladesh due to their low latitude. Studies over Europe and the U.S. would include cool season events characterized by deep mid-level troughs with strong flow throughout the troposphere, sufficient CAPE and relatively low LCL heights. In Bangladesh, the range of environmental conditions for significant tornadoes is less than U.S. and Europe due to the absence of cool season events. These events may be classified as relatively high CAPE (particularly in the 0–3 km AGL layer), sufficiently large deep-layer shear along with low LCL height and, crucially, low-level shear that is augmented by deviant (to the right of the mean flow) storm motion and/or propagation along a low-level convergence boundary. This environment has been documented in the U.S. (Hodanish and Davies, 2002; Davies, 2002) but is hypothesized that this type of environment occurs frequently in Bangladesh due to their low latitude.

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Appendix A

Table A1
Compilation of documented tornado events in Bangladesh and east India from 1838 to 2005. Highlighted rows indicate events simulated for the near-storm environment analysis. Time is given in Bangladesh Standard Time (BST). Direction is the direction the tornado moved in degrees (i.e. 0 indicates movement towards the south). Criteria refers to the numbered thresholds used to determine if the event was tornadic listed in Section 2a. Reference indicates the source of information, either articles cited in the References section or media reports with key listed below.

Date (MM/DD/YYYY)	Time (BST)	Fatalities	Direction	Criteria	Reference
04/08/1838	1330	215	330	1,4,5	Floyd (1839)
05/01/1865	1800	20	225	1,5	Goldar et al. (2001), Saha (1971)
04/15/1872	N/A	3	N/A	1	Saha (1971), Pedler (1888)
03/26/1875	Dusk	N/A	225	1,2	Petersen and Mehta (1981), Saha (1971), Pedler (1888)
03/31/1875	N/A	Many	N/A	1	Goldar et al. (2001), Petersen and Mehta (1981), Saha (1971)
03/27/1888	Sunset	4	340	1,4	Petersen and Mehta (1981), Pedler (1888)
03/27/1888	N/A	20+	N/A	5	Petersen and Mehta (1981), Pedler (1888)
04/07/1888	1900	118	320	1,2,3,4,5	Goldar et al. (2001), Pedler (1888)
04/07/1888	1930	70	330	1,2,3,4,5	Pedler (1888)
04/27/1888	2000	7+	150	1,2	Petersen and Mehta (1981), Pedler (1888)
04/29/1895	1530	24	N/A	5	Goldar et al. (2001)
4/12/1902	N/A	88	N/A	5	BDG
3/28/1903	N/A	Many	N/A	1,4	Goldar et al. (2001)
4/29/1904	N/A	7	N/A	1	Goldar et al. (2001)
4/4/1927	1630	N/A	N/A	1,4	Goldar et al. (2001)
3/20/1951	1215	N/A	N/A	1	Bonerjee (1951)
5/2/1951	N/A	19	N/A	5	TOI
5/2/1951	N/A	25	N/A	2,4,5	TOI
5/12/1951	N/A	200	N/A	5	TOI, BASICS, EMDAT
3/13/1953	N/A	19	N/A	5	TOI
5/5/1954	1200	17	N/A	5	BDG
5/21/1959	1750	11	N/A	1,2,5	Sen and Gupta (1961)
3/18/1961	N/A	32	N/A	4,5	PO
3/19/1961	1600	210	270	1,4,5	PO
4/3/1961	N/A	62	N/A	1,5	PO
4/15/1962	1350	0	N/A	1	PO
3/10/1963	N/A	20	N/A	5	PO
4/19/1963	1650	300	300	1,2,3,4,5	Saha (1966), Nandi and Mukherjee (1966), PO
4/11/1964	1630	500+	40	2,4,5	PO, EMDAT
3/23/1965	N/A	15	N/A	5	ABP, BASICS
3/21/1967	N/A	2	N/A	2	PO
4/16/1967	N/A	77	N/A	4,5	Nepal Commoner, PO
4/17/1967	N/A	25+	N/A	5	ABP, PO
4/19/1967	N/A	12	N/A	4,5	PO
5/1/1967	1630	30+	N/A	1,3,4,5	PO
4/3/1968	1500	42	280	2	ABP, BO
4/11/1968	N/A	141	N/A	4,5	PO, BDG
3/21/1969	530	0	270	1,2	Mukherjee and Bhattacharya (1973), ABP
4/14/1969	1645	660	310	1,2,3,4,5	Mowla (1986), PO
4/14/1969	1715	263	300	1,2,3,4,5	Mowla (1986), PO
4/17/1969	N/A	15	N/A	5	PO
4/17/1969	N/A	37	N/A	5	PO
4/17/1969	1540	32	N/A	5	PO
4/28/1969	N/A	8	N/A	2	PO
4/13/1970	1600	37	N/A	2,5	PO, BASICS
4/1/1972	1830	200+	N/A	1,2,4,5	Petersen and Mehta (1981), BO
4/5/1972	1650	75	N/A	2,3,4,5	BO
4/29/1972	N/A	300	N/A	5	BO, BASICS
4/12/1973	1500	200	N/A	4,5	BO
4/14/1973	N/A	15	N/A	5	BO
4/17/1973	1445	681	320	1,2,4,5	Hasan (1986), BO
4/11/1974	N/A	100	N/A	4,5	Hasan (1986), BO
4/10/1976	1730	46	N/A	2,4,5	Hasan (1986), BO
5/8/1976	N/A	2	N/A	3	BO
5/9/1976	N/A	1	N/A	1	Hasan (1986), BO
3/31/1977	N/A	17	N/A	5	BO
4/1/1977	1600	500	N/A	3,4,5	Ahmed (1977), Ono (1997), BO
4/2/1977	N/A	111	N/A	4,5	BO
4/7/1977	N/A	2	N/A	1,2	Bhattacharya and Banerjeb (1980)
4/15/1977	1530	10	N/A	1,2	Bhattacharya and Banerjeb (1980)
4/16/1978	1630	173	340	3,4,5	Ghosh (1982), ABP, TOI
4/18/1978	1400	128	300	5	Petersen and Mehta (1995), Singh (1981), ABP
5/7/1979	N/A	5	N/A	1	EMDAT, BDG
3/1/1981	2100	15	N/A	4,5	BO

(continued on next page)

Table A1 (*continued*)

4/12/1981	Midday	200	0	1,4,5	BO, EMDAT, BASICS
4/17/1981	1430	120	0	3,5	Petersen and Mehta (1995), Singh (1985), BASICS, TOI
4/12/1982	N/A	23	N/A	5	BO
4/9/1983	N/A	16	N/A	5	BO
4/12/1983	Noon	50	N/A	1,5	ABP
4/23/1983	N/A	2	N/A	1	BO
4/24/1983	N/A	25	N/A	4,5	BO
4/14/1986	Evening	120	N/A	1,4,5	BO
4/26/1989	1830	1300	250	1,2,4,5	Grazulis (1993), Hossain and Karmakar (1998), BO
4/20/1990	N/A	76	N/A	5	Das (1994), Ono (1997), EMDAT
4/29/1990	N/A	19	N/A	5	Das (1994), Ono (1997), EMDAT
3/31/1991	Evening	18	N/A	5	Ono (1997), BO
5/7/1991	Afternoon	45+	N/A	1,2,4,5	Ono (1997), BO, EMDAT
5/18/1991	N/A	50	N/A	5	Ono (1997), BO, EMDAT
4/22/1992	N/A	25	N/A	5	Ono (1997), BO
4/9/1993	1530	145	250	2,5	Misra (1996), BASICS
5/13/1993	1645	50	N/A	5	Ono (1997), BO
4/8/1995	N/A	40+	N/A	4,5	BO
5/13/1996	1630	700+	330	1,2,3,4,5	Schmidlin and Ono (1996), BO, BASICS, EMDAT
3/24/1998	1500	250	N/A	1,4,5	BASICS, EMDAT
4/8/1998	0800	21	N/A	5	BO
5/4/2003	N/A	30	N/A	5	The Telegraph (Calcutta)
4/14/2004	1230	111	N/A	1,5	Paul and Bhuiyan (2004), Daily Star, Reuters
3/20/2005	N/A	50	N/A	4,5	United News of Bangladesh

Key:

BO	Bangladesh Observer
PO	Pakistan Observer
ABP	Amrita Bazar Patrika
BDG	Bangladesh District Gazetteers
TOI	Times of India
BASICS	British Association for Immediate Care[3]
EMDAT	International Disaster Database[4]

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