Building Thunderstorm Resilience in the Hindu Kush Himalaya Region through Probabilistic Forecasts and Satellite Observations

Jonathan L. Case, Patrick N. Gatlin, Jayanthi Srikishen, Bhupesh Adhikary, Md. Abdul Mannan, and Jordan R. Bell

ABSTRACT: Some of the most intense thunderstorms on Earth occur in the Hindu Kush Himalaya (HKH) region of southern Asia—where many organizations lack the capacity needed to predict, observe, and/or effectively respond to the threats associated with high-impact convective weather. As a result, a disproportionately large number of casualties and damage often occur with premonsoon severe thunderstorms in this region. To address this problem, we combined ensemble numerical weather prediction (NWP), satellite-based precipitation products, and land-imagery techniques into a High-Impact Weather Assessment Toolkit (HIWAT) customized for HKH. In 2018 and 2019 demonstrations, a regional convection-allowing ensemble NWP system was configured to provide real-time probabilistic guidance of thunderstorm hazards over HKH, applying ensemble techniques developed for U.S.-focused experiments. Case studies of damaging wind, large hail, lightning, a rare Nepalese tornado, and landfalling tropical cyclone events show how HIWAT efficiently packages ensemble output into products that are readily interpreted by forecasters in HKH. Precipitation and total lightning flash verification reveal the highest skill occurred where deep convection was most frequently observed in Bangladesh and northeastern India, and verification scores exceeded global ensemble scores for heavy precipitation rates. These results demonstrate that plausible forecasts of thunderstorm hazards can be attained with relatively low computational resources, thereby facilitating advancements in extreme weather forecasting services in historically underserved regions such as HKH. In early 2022, a custom version of HIWAT was installed at the Bangladesh Meteorological Department using in-house computational resources, providing regional ensemble forecast guidance in real time.

KEYWORDS: Asia; Convective storms/systems; Severe storms; Ensembles; Short-range prediction; Decision support

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Some of the most intense thunderstorms on Earth occur in the Hindu Kush Himalaya (HKH) region of South Asia (Zipser et al. 2006; Romatschke et al. 2010) — where many organizations lack the capacity needed to predict, observe, and/or effectively respond to the threats associated with high-impact convective weather. Among the hazards include tornadoes, damaging straight-line winds (known as nor’westers in the HKH region), large hail, and flash flooding, which typically peak in the pre-wet-monsoon season (approximately March–May; Das et al. 2014). The HKH region south of the Tibetan Plateau experiences favorable conditions for frequent severe weather occurrence during the premonsoon when enhanced mid- to upper-level tropospheric flow combines with increasing low-level moisture and instability (sometimes extreme, with CAPE exceeding 5,000 J kg$^{-1}$). Mesoscale foci such as outflow boundaries off the Khasi Hills of northeast India and eastward-propagating drylines from the Indian subcontinent serve to initiate severe convection and also enhance low-level storm-relative helicity and storm organization, as discussed in Bikos et al. (2016). Previous studies have documented a disproportionately large number of casualties associated with intense thunderstorms in HKH (e.g., Bikos et al. 2016; Bista 1989; Dewan et al. 2017). The region is particularly vulnerable to lightning, with numerous casualties and fatalities each year (e.g., Dewan et al. 2018, 2017; Holle et al. 2019, 2018), including hundreds of fatalities during 2018–19. As a result, the Government of Bangladesh has recently declared lightning as a national disaster. Therefore, an important objective of our project’s initiative is to increase situational awareness and prediction capacity of these hazards to help reduce casualties in the HKH region.

Since meteorological observations are relatively sparse and there is limited access to operational weather radar datasets in Nepal and Bangladesh, it can be challenging to assess environmental conditions and resultant storm modes responsible for damaging thunderstorms across this region. Satellite observations, synoptic-scale reanalysis, and high-resolution regional modeling have been used to develop and refine conceptual models that explain deep convective storm patterns and behaviors in the region (e.g., Hirose and Nakamura 2005; Houze et al. 2007; Medina et al. 2010). Convection-allowing model (CAM) simulations have been used to investigate the mesoscale environment and resultant storm modes associated with high-impact tornadoes, hailstorms, and flash flooding in Nepal, Bangladesh, and northeast India (Litta et al. 2012; Bikos et al. 2016; Karmakar et al. 2017; Das et al. 2020; Meyer et al. 2021). These studies demonstrate that even CAMs at ~4-km grid spacing can sufficiently simulate the key ingredients responsible for severe convective events, including Nepal’s first documented tornado (Meyer et al. 2021).

The purpose of this study is to evaluate a multifaceted set of satellite and numerical weather prediction (NWP) tools focused on deep convective storms that plague the HKH region. Coined the High-Impact Weather Assessment Toolkit (HIWAT), this utility was developed under the auspices of a NASA Applied Sciences Capacity Building project, SERVIR, to improve the capacity of extreme weather services in the HKH region (Gatlin et al. 2021).
The short-term NWP strategies employed within HIWAT include developing real-time regional CAM ensemble guidance, similar to previous Spring Experimental Forecast Program campaigns at the NOAA Hazardous Weather Testbed (e.g., Clark et al. 2012), as well as the retired National Center for Atmospheric Research experimental ensemble prediction system (Schwartz et al. 2015, 2019). The HIWAT generates daily NWP simulations over a targeted area of the HKH region, focusing on Nepal, Bangladesh, and northeastern India. The system consists of ensemble-based forecast products similar to the High Resolution Ensemble Forecast (HREF) at the National Centers for Environmental Prediction (NCEP) Storm Prediction Center (Roberts et al. 2020; Jirak et al. 2012; Roberts et al. 2019) to offer guidance on the most likely areas of severe weather hazards for a 1–2-day forecast period. The observational components of HIWAT include satellite products from the Global Precipitation Measurement (GPM) mission (Hou et al. 2014; Skofronick-Jackson et al. 2017) and land-cover processing techniques (Bell and Molthan 2016; Bell et al. 2019; Molthan et al. 2014) that have been primarily used for case studies and validation of the HIWAT forecasts.

This article presents the implementation of a real-time ensemble forecasting experiment over the HKH region during the premonsoon months of 2018 and 2019, case studies for selected severe weather events, and quantitative validation of precipitation and lightning ensemble forecasts during 2018 and 2019. The system has been evaluated by national hydrometeorological agencies in the HKH region and found to be valuable in experimental operations. The paper is organized as follows: the NWP modeling platform and ensemble configuration are presented, the product suite and verification methods are described, results of severe weather events and precipitation/lightning verification are presented, and the paper concludes with a summary and discussion of transition activities to HKH hydrometeorological agencies.

**NWP model and ensemble configuration**

A virtual computing cluster in a cloud-like environment was established to support a regional CAM ensemble over south-central Asia. We applied the Unified Environmental Modeling System (UEMS; available online at http://strc.comet.ucar.edu/software/uems/) as the NWP software for an experimental forecasting experiment during spring 2018 and 2019. Maintained by the NOAA/NWS Science Operations Officers/Science and Training Resource Center, the UEMS consolidates the community Weather Research and Forecasting (WRF) NWP modeling system (Powers et al. 2017; Skamarock et al. 2008) into a streamlined open-source package for quickly and easily installing, configuring, and executing the WRF Model on a Linux-based operating environment, which is ideally suited to a cloud computing infrastructure.

The ensemble model configuration had an objective to provide 2 days of real-time forecast guidance of premonsoon thunderstorm hazards via a CAM nested-grid configuration. Given the available computational environment, the scientific/real-time objectives of the project, and the results of several studies that suggest diminishing returns with increased CAM ensemble sizes/sources (Clark et al. 2011; Schwartz et al. 2014; Jirak et al. 2016), we chose a 12-member ensemble system as a viable experimental solution. Each ensemble member ran separately on its own dedicated 32-core node, with auto postprocessing conducted on a dedicated “head” node for a 13-node computational configuration.

The model domain was designed to provide CAM guidance in a nested grid covering Nepal, Bangladesh, Bhutan, and northeastern India. The resulting 12-/4-km mesh grid is shown in Fig. 1, with configuration details common to each ensemble member summarized in Table 1. We varied both the initial/boundary conditions and physical parameterizations for achieving spread in the ensemble system. By varying select parameterization schemes, we can also glean information on the importance of certain parameterized physical processes in the
complex terrain of the Himalayas. We varied the planetary boundary layer (PBL) and microphysics (MP) parameterization schemes to account for important physical processes leading up to and following convective initiation.

A daily initialization at 1800 UTC and a 48-h integration length with hourly output frequency was applied to 1) provide several hours of model spinup prior to local sunrise (~0000 UTC) leading into the first diurnal heating cycle, and 2) capture two full diurnal heating cycles for day-1 and day-2 thunderstorm guidance. The first ensemble member was initialized with the NCEP/Environmental Modeling Center (EMC) Global Forecast System (GFS; Han and Pan 2011; Zhou et al. 2017) while members 2–12 were initialized with arbitrarily selected members of the EMC Global Ensemble Forecast System (GEFS; Guan et al. 2015, 2019; Li et al. 2019; Zhou et al. 2017; Zhu et al. 2018), as indicated in Table 2. While suboptimal due to errors associated with 6-h GEFS forecasts, we expedite the ensemble system product generation by using the previous cycle of the GFS/GEFS (i.e., 1200 UTC) for initial and boundary conditions for the UEMS/WRF runs. Future improvements could include implementing a regional data assimilation and perturbation methodology to improve initial conditions of the ensemble system.

**Product suite and model validation**

**Environmental indices, proxy fields, and ensemble products.** We utilized the open-source Sounding and Hodograph Analysis and Research Program in Python (SHARPpy; Blumberg et al. 2017; Halbert et al. 2015) to generate multivariate composite indices from the first ensemble member to assess the environmental conditions favoring severe convection (e.g., super-cell composite parameter, significant tornado parameter, etc.). Following Kain et al. (2010), ensemble products were developed based on proxy simulated fields representing specific convective hazards. The ensemble suite included derived products similar to CAM ensembles in the continental United States (Clark et al. 2012; Schwartz et al. 2015;
such as postage stamp displays, ensemble mean, minimum and maximum spread, paintball plots, neighborhood probability (Schwartz and Sobash 2017), and probability matched mean (PMM; Ebert 2001; Clark 2017). For computing neighborhood probabilities, we applied a neighborhood box with a 20-km half-width to convective hazards with small spatial footprints, such as updraft helicity, derived lightning flashes, vertically integrated graupel cores, and localized regions of high 10-m winds. All of the products were generated at hourly intervals and 24-h daily temporal composites, with a summary provided in Table 3. In addition, all real-time and archived ensemble and deterministic product imagery from 2018 to 2022 were made available on the HIWAT Model Viewer at https://hmv.servirglobal.net/ (see data availability statement at end of this manuscript).

Table 2. Matrix of initial/boundary conditions, and planetary boundary layer (PBL) and microphysics (MP) parameterization schemes comprising the 12-member ensemble system. PBL schemes: YSU (Yonsei University; Hong et al. 2006), MYJ (Mellor–Yamada–Janjic; Janjic 1994, 2001), and MYNN2 (Mellor–Yamada–Nakanishi–Niino Level 2.5 closure; Nakanishi and Niino 2009). MP schemes: Godd (Goddard 6-class cumulus ensemble with graupel; Lang et al. 2011, 2007; Tao et al. 2003, 2014), Lin 6-class [Lin et al. (1983); Thompson from 1 to 28 Mar 2018 (Thompson et al. 2008)], WSM6 [WRF Single-Moment 6-class (Hong and Lim 2006)], and Morr [Morrison double-moment; Morrison et al. (2009)]. Ensemble members are shown in bold font, and initial conditions are shown in italics. We initially ran with the Thompson microphysics scheme from 1 to 28 Mar 2018, but the Thompson ensemble members became consistently unstable with deep moist convention, so we changed to Lin microphysics on 29 Mar 2018, onward.

![Table 2](https://example.com/table2.png)

Validation of events, precipitation, and lightning. Validation of damaging thunderstorm events is highly dependent on an accurate compilation of damage reports from the field, Roberts et al. 2019), such as postage stamp displays, ensemble mean, minimum and maximum spread, paintball plots, neighborhood probability (Schwartz and Sobash 2017), and probability matched mean (PMM; Ebert 2001; Clark 2017). For computing neighborhood probabilities, we applied a neighborhood box with a 20-km half-width to convective hazards with small spatial footprints, such as updraft helicity, derived lightning flashes, vertically integrated graupel cores, and localized regions of high 10-m winds. All of the products were generated at hourly intervals and 24-h daily temporal composites, with a summary provided in Table 3. In addition, all real-time and archived ensemble and deterministic product imagery from 2018 to 2022 were made available on the HIWAT Model Viewer at https://hmv.servirglobal.net/ (see data availability statement at end of this manuscript).

Table 3. Multiparameter environmental indices, model convective proxies, and ensemble fields implemented as part of the HIWAT product suite.

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which is a work in progress for the HKH region. We consulted available media (typically local and regional news outlets) and corresponded with collaborators in Nepal, India, and Bangladesh to document observed casualties and damage reports for select events (Gatlin et al. 2021). However, accurately documenting severe weather events and associated casualties remains an ongoing challenge in the HKH region.

Quantitative precipitation forecasts (QPF) were validated for individual ensemble members, the ensemble mean, and PMM against the final research-quality version 06B of the Integrated Multi-satellitE Retrievals for GPM (IMERG) half-hourly rain-rate product (Huffman et al. 2020; Tan et al. 2019). Half-hourly precipitation rates were combined into hourly quantitative precipitation estimates (QPE), then summed across accumulation intervals to compute skill scores using traditional contingency table verification methods. The Model Evaluation Tools (MET; Brown et al. 2020) verification package was utilized to compare the model QPF to IMERG QPE using a 20-km neighborhood window consistent with that applied to generate the ensemble probabilities. To benchmark the HIWAT QPF verification scores, we compared validation results against 12 GEFS members. Numerous metrics are available from the MET output, but we focused on Heidke skill score (HSS) for brevity’s sake, since this metric conveys model accuracy by taking into account correct forecasts due to random chance. Forecasts demonstrate skill over random chance when HSS is above 0, with perfect skill given by an HSS of unity.

Total lightning flashes from the Earth Networks Total Lightning Network (ENTLN) dataset (Bui et al. 2016; Heckman et al. 2014; Lapierre et al. 2019) served as ground truth for validating the lightning forecast algorithm (LFA; McCaul et al. 2009, 2020) simulated total lightning flash rates of each ensemble member. The ENTLN flashes were binned at ±10 min of the top of each hour, then gridded onto the 4-km model nested grid. The LFA flashes from each ensemble member were verified in a similar manner as QPF using a 20-km neighborhood window. However, given the uncertainties associated with both model-predicted lightning and the ENTLN detection efficiency in the region (Lapierre et al. 2019), we present only verification results for the occurrence of any lightning activity.

**Results of 2018 and 2019 forecasting experiments**

Over 300 people perished as a result of premonsoon intense thunderstorm hazards in India, Bangladesh, and Nepal during the 2018 experiment, primarily due to straight-line convective winds and lightning strikes (refer to reporting in Gatlin et al. 2021). The 2019 premonsoon season was generally less severe than 2018, but still experienced numerous casualties associated with a rare tornado event in south-central Nepal on 31 March 2019 (Shrestha et al. 2019), followed by numerous isolated lightning casualties, largely in Bangladesh. Additionally, Cyclone Fani brought numerous fatalities associated with damaging winds and flooding as it moved across the coastal areas of the northern Bay of Bengal into Bangladesh during early May 2019.

**Case studies of significant events.**

**30 March 2018 large hail and damaging straight-line winds.** The 30 March 2018 event exhibited a classic synoptic setup for severe weather across the HKH region. The combination of a warm and moist southerly low-level flow with strong to extreme instability, an elevated mixed layer and capping inversion advecting eastward from the Indian Subcontinent, strong deep-layer wind shear, and mesoscale outflow boundaries can lead to organized intense convection in the region (see Bikos et al. 2016; Dewan et al. 2018; Mannan et al. 2015; Yamane et al. 2013, 2010a,b; Yamane and Hayashi 2006). Also, a common occurrence is that midlevel wind maxima (~700–500-hPa layer) are diverted around the Himalayas due to the physical barrier of the high terrain, thereby enhancing the deep-layer directional and speed shear to the south of the Tibetan Plateau.
Select environmental fields in the 15-h forecast of ensemble member 1 (Fig. 2) summarize the midafternoon environment at 0900 UTC 30 March that was conducive to organized severe thunderstorm activity. A deep upper-level low resided over the Tibetan Plateau along with a substantial southwesterly subtropical jet streak at 200 hPa exceeding 80 kt ($1 \text{ kt} \approx 0.51 \text{ m s}^{-1}$) extending from central India across Bangladesh, Myanmar, and into southern China (Fig. 2a). A classic setup existed where the 500-hPa wind speeds were enhanced to the south of the Himalayas (Fig. 2b). At 850 hPa (Fig. 2c), a relatively weak southwesterly low-level jet ~20+ kt occurred across Bangladesh transporting low-level moisture from the Bay of Bengal. At the surface, rich moisture with 2-m dewpoints exceeding 24°C resided near the Bangladesh coast, with a lower dewpoint maximum above 18°C extending from northern Bangladesh into southeastern Nepal (Fig. 2d). A surface low center resided over eastern India with a trough/dryline extending south from the low pressure. The resulting surface-based convective available potential energy (CAPE; Fig. 2e) exceeded 3,000 J kg$^{-1}$ across portions of northern Bangladesh and northeastern India, reaching 5,000+ J kg$^{-1}$ over the southeastern Indian coast. The low-level shear given by the 0–3-km storm-relative helicity (SRH) was enhanced to the east and northeast of the surface low center across northern Bangladesh into southeastern Nepal (Fig. 2f). This combination of strong instability, 150–350 m$^2$ s$^{-2}$ low-level SRH, and strong wind shear favored intense organized convection across the region. Based on the simulated midafternoon supercell composite, significant tornado, and derecho composite parameters (not shown), there was an elevated threat for supercells with large hail and damaging straight-line winds across far southeastern Nepal and much of northern and central Bangladesh.

The Advanced Himawari Imager observations from Japan's Himawari-8 geostationary satellite (Bessho et al. 2016) and available storm reports in Fig. 3 show that the most intense convection tracked southeastward across northern and central Bangladesh between 0700 and 1100 UTC (Figs. 3a–c). The discrete nature of the intense thunderstorms on the Himawari true color enhanced imagery (Miller et al. 2016; Murata et al. 2018) is evident based on the distinct overshooting tops, breaks between high anvil cloud decks (especially before 1100 UTC), and sharp clearing outside of the storms, suggesting a dominant supercell convective mode. Storm reports in Fig. 3d show that predominantly large hail reports occurred across far northern and west-central Bangladesh, along with a high wind report in northeastern Bangladesh. Media reports indicated large hail (up to 7-cm diameter) penetrating roofs of homes across northern Bangladesh.

The ensemble forecast initialized on 1800 UTC 29 March captured fairly well the areas of lightning, large hail, and damaging convective winds observed in the 30 March event. The postage stamp view of the 12 ensemble members of composite LFA during the first 24 h of the forecast (Fig. 4) show a consistent pattern of widespread simulated total lightning across southeastern Nepal, much of central and northern Bangladesh, and portions of northeastern India. A more conditional lightning threat was indicated by the ensemble members across the southeast India coast, where forecast lightning activity was more scattered and not present in all ensemble members. The results of Fig. 4 suggest that the microphysics schemes play more of a role in determining the areal coverage of total lightning compared to the choice of PBL scheme, as seen by the greater overall coverage with the Goddard and Morrison schemes compared to the others (see McCaul et al. 2020). The resulting day-1 20-km neighborhood probability of lightning activity at any time during the first 24 h (Fig. 5a) indicate probability exceeded 90% across most of the northern half of Bangladesh, northeast India, and southeast Nepal. Observed total lightning activity composited during the same 24-h period from ENTLN (Fig. 5b) show a northwest-southeast pattern of lightning activity from Nepal into Bangladesh and northeastern India, quite similar to the pattern and orientation of the highest HIWAT day-1 lightning probabilities. The more conditional lightning threat along
Fig. 2. WRF/UEMS 15-h forecast environmental variables valid at 0900 UTC 30 Mar 2018 from ensemble member 1, which serves as a deterministic output solution in HIWAT. (a) Outer 12-km domain d01 200-hPa geopotential heights (m; dashed red lines), wind barbs (kt), and color-shaded wind speeds (kt). (b) As in (a), but at 500 hPa. (c) As in (a), but at 850 hPa (blue circle denotes region of weak low-level jet). (d) Nested 4-km domain (d02) 2-m dewpoint (°C), mean sea level pressure (hPa; red dashed lines), 10-m wind barbs (kt), and position of surface low pressure and accompanying dryline (red dashed lines). (e) Domain d02 surface convective available potential energy (CAPE; J kg⁻¹; color shaded) and convective inhibition (CIN; J kg⁻¹; contours). (f) Domain d02 0–3-km storm relative helicity (SRH; m² s⁻¹; shaded according to scale).
the southeast India coast near Kolkata did not verify in the observed ENTLN, which at the time had a detection efficiency ~50%–60% in this region of India and western Bangladesh (Lapierre et al. 2019).

The composite day-1 probability maps for the other convective hazards on 30 March are presented in Fig. 6. The threat for general deep convection is represented by probability of simulated reflectivity exceeding 50 dBZ (Fig. 6a), which indicated a high threat for deep convection across much of the same region as the lightning threat in Fig. 5a. The probability of 10-m wind speeds exceeding 50 kt (~25.7 m s⁻¹; Fig. 6b) had generally lower probabilities, with the highest probability across eastern Bangladesh not far from the observed wind damage report in Fig. 3d. The hail proxy threat given by the total column graupel exceeding 40 kg m⁻² showed the highest probabilities in two areas across central and northern Bangladesh (Fig. 6c), closely corresponding to the two areas of clustered large hail reports in Fig. 3d. Similarly, the highest probabilities of updraft helicity exceeding 100 m² s⁻² occurred across central and northern Bangladesh, and along an axis extending from southeast Nepal into northeast India. Oftentimes the updraft helicity
threat closely corresponds to the total column graupel (hail) threats because long-lived, rotating convective updrafts (i.e., mesocyclones or supercell thunderstorms associated with updraft helicity) often favor the growth of large hail aloft in thunderstorms (Knight and Knight 2001). These temporal daily composited probabilities of thunderstorm hazards can subsequently be examined in hourly forecasts to determine the most likely timing of each hazard, albeit limited by the skill of the overall ensemble system.

17 April 2018 Kolkata severe windstorm. On 17 April 2018, a severe windstorm associated with intense convection affected Kolkata, India, during the evening hours. Numerous fatalities and injuries occurred associated with downed trees from the severe thunderstorms in the Bengal state of India, as observed wind gusts peaked at 98 km h$^{-1}$ (~27 m s$^{-1}$; HT Correspondent 2018). The damage caused by this storm was observed first-hand by several coauthors of this manuscript, who traveled to Kolkata about a week after the storm and noted numerous billboards destroyed, as well as extensive large tree limbs downed across the city.
The Himawari-8 combined visible–IR imagery (Fig. 7) depicts the development of scattered convection to the northwest of Kolkata at 1000 UTC (Fig. 7a), which tracked southeastward over the next few hours (Figs. 7b–d). The most intense of the storms is evident over Kolkata at 1200 and 1300 UTC given by the bright white in Figs. 7c and 7d associated with cold cloud-top temperatures in the band-13 IR imagery.

The daily HIWAT probability forecasts of 10-m wind speed exceeding 40 kt (~20.6 m s\(^{-1}\); Figs. 8a,b) show that the day-2 forecast initialized at 1800 UTC 15 April was more aggressive in depicting higher probabilities of strong convective winds across southeastern India compared to the day-1 forecast initialized at 1800 UTC 16 April. However, despite some decrease in probability from day 2 to day 1, the maximum 10-m wind speed from any ensemble member at 1100 UTC (Figs. 8c,d) depicts the potential for localized 10-m winds of 60+ kt (31 m s\(^{-1}\)) near Kolkata in both ensemble runs, comparable to the observed intensity. The probability patterns for strong 10-m wind speed and maximum forecast values suggest a conditional threat of damaging winds dependent on the development of scattered convection.

The hourly progression from 0900 to 1200 UTC of PMM composite reflectivity and probability of 10-m winds exceeding 40 kt from the 15 April ensemble forecast is presented in Fig. 9. The composite reflectivity PMM represents the intensity resampling of the ensemble mean composite reflectivity from the combined probability density function of the individual ensemble members, thereby building back amplitude that tends to be washed out during the averaging process. Scattered convection organized and intensified across southeast India into southern Bangladesh in the reflectivity PMM between 0900 and 1200 UTC (Figs. 9a,c,e,g) as the simulated storms moved southeastward toward Kolkata and the Bay of Bengal coast. The relatively high probabilities of 10-m wind speeds exceeding 40 kt accompanied the reflectivity PMM evolution (Figs. 9b,d,f,h), with the highest probability indicative of the most intense simulated convection occurring west of Kolkata. Overall, the nature of the convective mode and character were well represented by the ensemble up to two days in advance for this high-end, relatively isolated convective event, albeit with some decreased skill in the day-1 forecast.
31 March 2019 South-Central Nepal Tornado. A rare documented tornado, rated as EF3 (wind speed between 180 and 265 km h⁻¹) on the Enhanced Fujita scale, impacted the Bara and Parsa districts in south-central Nepal during the evening of 31 March 2019 (Meyer et al. 2021). Thirty people were killed and over 1,150 injured (Shrestha et al. 2019) when a tornado tracked on a northwest–southeast path for about 35 km, leaving a damage scar across the region that is clearly visible from low-Earth orbit in the Sentinel-2 imagery shown in Fig. 10. In addition, six people were killed along with extensive property damage over western and central Bangladesh associated with a documented nor’wester (NIRAPAD 2019). The environmental conditions favoring severe convective winds and even tornado potential were depicted by the HIWAT deterministic (ensemble member 1) 36–42-h forecasts, as shown in Fig. 11. A strong midlevel wind maximum from a northwesterly direction at 700 hPa of ~40–50 kt is seen in the 36-h forecast valid 0600 UTC 31 March, several hours before the tornado occurred, and positioned unusually close to the Himalaya mountains across extreme southern Nepal and northeastern India (Fig. 11a). At the surface, a broad southeasterly flow advected a relatively moist air mass...
from the Bay of Bengal into southern and eastern Nepal, with 2-m dewpoint temperatures of 15\(^\circ\)–18\(^\circ\)C+ (Fig. 11b). The southeasterly flow underlying the northwest flow at midlevels led to large directional shear and a moderately strong low-level environmental helicity that contributed to the potential for rotating thunderstorms. The combination of moderate instability [most unstable CAPE (MUCAPE) ~1,500–2,500 J kg\(^{-1}\); Fig. 11c] and strong low- to midlevel shear led to a risk of rotating (supercell) thunderstorms across south-central Nepal, as seen in the SCP forecast from ensemble member one 42-h forecast valid at 1200 UTC 31 March (Fig. 11d), near the time of the tornado event. However, the forecast STP from the first ensemble member remained less than one leading up to the tornado event (not shown).

The day-2 composite probability products also indicated the potential for rotating thunderstorms and damaging straight-line winds in central Nepal (red circled areas in Figs. 11e,f). The probability of updraft helicity exceeding 50 m\(^2\) s\(^{-2}\) was relatively low across central Nepal compared to the high probabilities across northern Bangladesh and northeast India; however, a secondary maximum of probability > 50% extended northwestward into central Nepal, indicating a nontrivial threat for rotating updrafts in convective storms on 31 March (Fig. 11e). Also worth noting is the secondary axis of high probability for damaging winds across southeastern India (Fig. 11f) coinciding with near zero probability in updraft helicity (Fig. 11e), suggesting mainly a damaging straight-line wind threat there. However, no storm reports from India were identified for this day.

Similarly, the potential for damaging straight-line winds was present across central Nepal according to the day-2 composite probability of 10-m wind speeds exceeding 40 kt (Fig. 11f). Again, the highest probabilities for damaging convective winds occurred over India and Bangladesh, but a secondary maximum of probabilities greater than 50% is seen over central Nepal, in the vicinity of where the tornado occurred. In fact, the simulated timing and location of convective initiation for the responsible storms was nearly coincident in many members to the observed initiation as documented by Shrestha et al. (2019); however, the model runs...
did not sustain this deep convection long enough. Similar to the Kolkata windstorm event of 17 April 2018, this event saw HIWAT probabilities diminish somewhat from the day-2 to day-1 forecasts.

**Cyclone Fani: Early May 2019.** The primary focus of this ensemble forecasting system is on premonsoon severe convection; however, the ensemble and probability products also demonstrated utility for tropical cyclone forecast scenarios, such as with Cyclone Fani of early May 2019. Cyclone Fani developed in the southern Bay of Bengal and intensified to an equivalent category 4 hurricane on the Saffir–Simpson scale [winds > 209 km h⁻¹ (58 m s⁻¹)] across the west-central Bay of Bengal. The cyclone made landfall across southeastern India causing extensive damage and impacts (see Indian Red Cross Society 2019; Wikipedia 2019), before weakening as it tracked inland into western Bangladesh (Fig. 12). The primary impacts on Bangladesh included storm surge along the coast to the east of the cyclone center,
Fig. 9. Hourly composite reflectivity (a),(c),(e),(g) probability matched mean (PMM; dBZ) and (b),(d),(f),(h) probability of 10-m wind speed exceeding 40 kt within 20 km of a location (%) from the ensemble initialized at 1800 UTC 15 Apr 2018. The 39–42-h forecasts are shown, valid 0900–1200 UTC 17 Apr. Reference cities/landmarks and sounding sites are denoted by stars and circles, respectively.
flooding, and high winds. Although not known to have occurred with Fani, tropical cyclones that recurve northeastward can sometimes produce mini tornado outbreaks (e.g., McCaul 1991, 1987) that cause further severe damage, albeit more localized than the broader cyclone impact, and several ensemble members depicted a corridor of updraft helicity swaths across southern and central Bangladesh associated with Fani’s landfall.

In this event, we focus on two specific ensemble products: 1) the maximum 10-m wind speed from all ensemble members and 2) the probability of 10-m wind speed exceeding 40 kt. As illustrated in Fig. 13, these two products provide information about the potential variability and uncertainty in Cyclone Fani’s track and accompanying potential wind impact, as well as the reduction in high wind probabilities as the cyclone weakened during its forecast track across Bangladesh. The maximum 10-m wind speed at forecast hours 30, 36, and 42 from the ensemble cycle initialized at 1800 UTC 2 May 2019 (Figs. 13a,c,e) depict the forecast variability of Cyclone Fani by the ensemble members, as can be gleaned through multiple circular wind maxima. The contributing ensemble members that simulated the center of Fani closer to the coast retained the highest wind speeds (especially over water), whereas the other circular wind maximum further inland were more ill defined and weaker in magnitude. The overall trend of all ensemble members during these 12 h was for rapid weakening in maximum 10-m wind speeds from ~60–70+ kt at forecast hour 30 (Fig. 13a) to ~45–55 kt by forecast hour 42 (Fig. 13e). A similar trend occurred in the probability of 10-m wind speed exceeding 40 kt (Figs. 13b,d,f). At forecast hour 30 (Fig. 13b), the probability of exceeding 40 kt was greater than 80% across the southeast coastal area of India and adjacent waters. These probabilities decreased to ~50%–60% across portions of southern Bangladesh by forecast hour 36 (Fig. 13d) and then less than 40% with greatly diminished spatial coverage by forecast hour 42 (Fig. 13f). These select ensemble products highlighted in Fig. 13 indicate the potential utility of applying some of the convective ensemble diagnostics to tropical cyclone forecast scenarios in this region.

**Precipitation and total lightning verification.** Select precipitation and lightning verification results are given in Figs. 14 and 15. The 2018 premonsoon 6-h accumulated precipitation Heidke skill score (HSS) at 25+-mm intensity indicates that the HIWAT ensemble members had the highest overall skill in forecasting heavy precipitation in the day-1 time frame over

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Fig. 10. European Space Agency’s Copernicus Sentinel-2 30-m resolution images at 0525 UTC 1 Apr 2019 centered over south-central Nepal, depicting the ~35-km-long tornado damage path evident in (a) a true color image, and (b) a false color composite image utilizing the shortwave infrared channel that helps highlight the moisture content in vegetation. Arrows denote the approximate tornado path while the solid line indicates the Nepal–India border. Images contains Modified Copernicus Sentinel data 2021/Sentinel Hub.
Fig. 11. Deterministic (from ensemble member 1) and probabilistic fields from the ensemble initialized at 1800 UTC 29 Mar 2019: (a) 12-km outer grid 700-hPa 36-h forecast winds (kt) valid 0600 UTC 31 Mar, (b) 4-km nest 2-m dewpoint (°C) and 10-m wind (kt) 36-h forecast valid 0600 UTC 31 Mar, (c) regional zoom of 12-km grid 36-h forecast most unstable CAPE (MUCAPE; J kg$^{-1}$) valid 0600 UTC 31 Mar, (d) regional zoom of 12-km grid 42-h forecast supercell composite parameter (SCP) valid 1200 UTC 31 Mar, (e) day-2 ensemble probability summary (%; 25–48-h forecasts valid 1800 UTC 30 March–1800 UTC 31 March) of 2–5-km updraft helicity exceeding 50 m$^2$ s$^{-2}$ within 20 km of a location, and (f) day-2 ensemble probability summary (%; 25–48-h forecasts) of 10-m wind speed exceeding 40 kt within 20 km of a location. Red circles in (e) and (f) highlight the area of interest in central Nepal. Reference cities/landmarks and sounding sites are denoted by stars and circles, respectively, in (e) and (f).
Bangladesh (blue shaded boxplots in Fig. 14a, bottom right), where the distribution of HSS scores approached 0.4 for many ensemble members and for the PMM. The HSS results were generally between 0.2 and 0.3 in the more mountainous countries of Nepal and Bhutan (top row of Fig. 14a), and around 0.3+ over northeastern India. Interestingly, Nepal and Bhutan experienced the greatest intermember variability in skill among the four countries, suggesting that the choice of model physical parameterization schemes may be more important in areas of complex terrain during the premonsoon. In fact, an examination of the individual scores comprising the boxplots reveal that the microphysics schemes largely contributed to the variability in verification during the 2018 premonsoon months in Nepal. In general for most countries, the day-2 precipitation skill is comparable to or slightly lower than the day-1 skill except for Bangladesh, which experienced the largest drop in HSS between the day-1 and day-2 forecasts. The PMM (orange dots) generally had competitive or higher skill relative to the individual ensemble members, as should be the case. The HSS results for the 2019 premonsoon season (Fig. 14b) have slightly lower scores overall, but support the same conclusions. When compared to GEFS member verification scores (red boxplots in Fig. 14), the HIWAT members had superior skill at this higher precipitation rate threshold (as expected), since higher model resolution is crucial in areas of complex terrain. When verifying lower-intensity thresholds (e.g., 1 and 5 mm per 6 h), the GEFS and HIWAT members had more comparable skill.

The same analysis of HSS scores for the 2018 and 2019 premonsoon season total lightning forecasts are given in Fig. 15. As previously mentioned, we are only examining the occurrence of any lightning during the 24-h day-1 and day-2 intervals. The results indicate that the highest overall skill in predicting lightning occurred over Bangladesh (lower right) whereas the lowest skill was found in Bhutan (upper right), with very marked differences in these countries’ scores. The most likely explanation for this behavior is that the frequency of lightning is much higher over Bangladesh compared to Bhutan, which is supported by satellite-based lightning studies (e.g., Cecil et al. 2014). Similar to the precipitation HSS, we see the largest decline in lightning forecast skill over Bangladesh from day-1 to day-2 in both premonsoon seasons, likely due to the more highly variable nature of propagating convective systems dependent on synoptic and mesoscale forcing features that can be more uncertain as forecast time increases. The skill is more similar from day-1 to day-2 in Nepal and Bhutan because of the dominant topographic forcing that drives precipitation and lightning production in these areas (e.g., Barros et al. 2004; Houze et al. 2007; Medina et al. 2010; Romatschke and Houze 2011). The HSS scores for northeastern India (Fig. 15; lower-left panel) lie between that of Bangladesh and Nepal. It is interesting to note that the ensemble intermember skill variability for lightning is not nearly as large as the variability in forecasting heavy precipitation in the countries with the most complex terrain (Nepal and Bhutan), suggesting that the LFA algorithm is not...
Fig. 13. Six-hourly sequence of (a),(c),(e) maximum 10-m wind speed from all ensemble members and (b),(d),(f) probability (%) of 10-m wind speed exceeding 40 kt within 20 km of a location from the WRF Model ensemble forecast initialized at 1800 UTC 2 May 2019. Forecast hours shown are 30, 36 and 42, valid at 0000, 0600, and 1200 UTC 4 May, respectively. Reference cities/landmarks and sounding sites are denoted by stars and circles, respectively.
Fig. 14. Boxplot distributions of Heidke skill score for 25+ mm (6 h)$^{-1}$ accumulated precipitation within 20 km of a location for (a) 2018 and (b) 2019 premonsoon months of March–May (MAM), validated against GPM/IMERG-Final QPE and masked by country. Boxplot distributions comprise the 4-km nested grid of the 12 HIWAT members in blue shading, along with 12 GEFS members in red shading (GEFS member 1 plus the 11 used to initialize HIWAT members 2–12). Skill scores of the ensemble mean (EM) and probability matched mean (PMM) are also indicated by green and orange dots, respectively.
as sensitive to (micro)physics parameterization choice as is the overarching precipitation production. So despite the inferred LFA coverage variability as a function of microphysics scheme in Fig. 4 for the 30 March 2018 event, the bulk verification scores suggest that the ensemble members have similar skill in diagnostic lightning activity during the premonsoon months. In general, the skill in forecasting any lightning activity during the premonsoon seasons was comparable to, or slightly less than the skill in predicting heavy rainfall within a 24-h period, except in Bhutan where the lightning skill was lowest (not shown).

**Summary and transition activities**

This paper presented an experimental–operational CAM ensemble forecasting system configured for the HKH region of south-central Asia. The focus and objectives have been to increase situational awareness and provide a computationally affordable prototype that can enable probability forecasts of specific hazardous convective phenomena during the synoptically active premonsoon season. The HKH ensemble was tailored to emulate similar CAM ensemble systems in the U.S. in order to provide guidance in forecasting threats of damaging straight-line winds, hail, supercells/tornadoes, lightning, and flash flooding. A 12-member solution was developed using the WRF NWP modeling system and a nested domain configuration with 12- and 4-km horizontal grid spacing. In addition to the ensemble suite of products, the first ensemble member also provided deterministic forecast guidance, including geographical subsets of severe weather indices that combine shear, instability, and
other relevant environmental factors into normalized parameters that effectively convey the threat of supercells, significant tornadoes, damaging wind, and hail. Several high-impact case studies were presented in this paper to describe the potential range of applications of the ensemble system. While the exact placement and timing of convection is not typically expected to match observations in CAMs, the overall ensemble depiction of the nature and character of simulated severe thunderstorm elements was reasonably well captured in the cases highlighted herein. These select cases and other events not shown suggest that this relatively simple configuration of a CAM ensemble system can provide added value to the forecast process and enhanced situational awareness in the HKH region associated with premonsoon organized convection, and even tropical cyclone forecast impacts.

Composite verification results of precipitation and lightning from the 2018 and 2019 premonsoon seasons revealed that day-1 forecasts had the highest skill over Bangladesh and that the greatest intermember variability in skill was seen in precipitation forecasts over Nepal, suggesting sensitivity to and importance of physical parameterization selection in areas of complex terrain. Both precipitation and lightning forecasts proved most skillful during the most convectively active portions of the diurnal cycle. Despite bulk verification scores generally showing more skill on day 1, we noted that at times HIWAT depicted larger day-2 hazard probabilities for some high-impact events, which is worth investigating in greater detail for future analysis.

This manuscript focused on the premonsoon seasons, but HIWAT was extended into the wet monsoon months from 2018 to 2022 at the request of hydrometeorological organizations to help assess the flooding threat during the wet monsoon. The hourly PMM fields have been used each day as input into hydrological models for providing guidance on streamflow and inundation potential (Nelson et al. 2019). The 2018–19 demonstration of HIWAT provided forecasters at the Bangladesh Meteorological Department (BMD) and Nepal’s Department of Hydrology and Meteorology (DHM) with new information to enhance their early warning services in the region, in particular as they pertain to forecasting hazards associated with severe convective weather. In early 2022, a customized version of the ensemble forecasting system was installed onto a high-performance computing platform procured by BMD specifically for running HIWAT in-house and incorporating its guidance into their forecast process. The adoption of HIWAT by BMD represents a research-to-operations and capacity-building success for the SERVIR program in the HKH region, helping to meet the need of thunderstorm hazard forecasting capabilities for the protection of life and property.

Although we presented promising examples of several high-impact weather events, the system would benefit from additional testing and evaluation with the aid of a centralized storm reporting and archiving system to perform such studies. The thresholds applied in the probabilistic products may need further refinement so they are more appropriate to the region(s) of interest. For example, convection in the higher terrain of Nepal likely produces damaging hail at lower reflectivity and/or vertically integrated graupel thresholds than storms in Bangladesh, which tend to be deeper and have a higher melting level. However, these adjustments are not limited to the product configuration, but also extend to the model configurations. Further investigation to assess the impact of physical parameterizations and perform quantitative comparisons with satellite, radar and in situ observations will benefit forecaster understanding of individual modeling member accuracy and the ensemble output representativeness.

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**Data availability statement.** The datasets used to generate the regional ensemble forecasts include personal tiles of the 0.25° resolution GFS model forecasts at 3-hourly intervals, and 0.50° resolution GEFS modeling members at 3–6-hourly intervals for initial and boundary conditions. The GFS and GEFS model archives are available from the National Centers for Environmental Information and are also archived on the project computing infrastructure. Output of UEMS/WRF Model simulations and derived ensemble products are archived on the cloud-like infrastructure from 2018 to present (March–August/September each year), with the intent of enabling open science by providing the data to the general public, university researchers, meteorological organizations, and decision-makers through open-access via a NASA DAAC and/or cloud platform. The GPM/IMERG-Final dataset for rainfall estimates and total lightning flashes are available from the NASA GPM project archive and Earth Networks, respectively. Both real-time and archived forecast imagery are available on the HIWAT Model Viewer page (https://hmv.servirglobal.net/), which includes deterministic output from ensemble member 1 and ensemble fields and probabilities for each daily forecast. An example of the HIWAT Model Viewer is shown in Fig. A1 of the appendix, displaying the total accumulated precipitation PMM from an excessive rainfall event in northeastern India during mid-May 2022.
Appendix: HIWAT Model Viewer Visualization Repository
All daily ensemble model imagery are archived to the HIWAT model visualization repository available at https://hmv.servirglobal.net. A screen capture of the user interface given in Fig. A1.

Fig. A1. HIWAT Model Viewer showing the 54-h total accumulated precipitation PMM from the ensemble initialized at 1200 UTC 15 May 2022. The HIWAT Model Viewer is available online at https://hmv.servirglobal.net/.
References


