Extreme Snow Events along the Coast of the Northeast United States: Analysis of Observations and HiRAM Simulations

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ABSTRACT

This study used both observations and global climate model simulations to investigate the characteristics of winter extreme snowfall events along the coast (the Interstate 95 corridor) of the northeast United States where several mega-cities are located. Observational analyses indicate that, during 1980–2015, 110 events occurred when four coastal cities—Boston, New York City, Philadelphia, and Washington, D.C.—had either individually or collectively experienced daily snowfall exceeding the local 95th percentile thresholds. Boston had the most events, with a total of 69, followed by 40, 36, and 30 (moving southward) in the other three cities. The associated circulations at 200 and 850 hPa were categorized via *K*-means clustering. The resulting three composite circulations are characterized by the strength and location of the jet at 200 hPa and the coupled low pressure system at 850 hPa: a strong jet overlying the cities coupled with an inland trough, a weak and slightly southward shifted jet coupled with a cyclone at the coast, and a weak jet stream situated to the south of the cities coupled with a cyclone over the coastal oceans. Comparative analyses were also conducted using the GFDL High Resolution Atmospheric Model (HiRAM) simulation of the same period. Although the simulated extreme events do not provide one-to-one correspondence with observations, the characteristics nevertheless show consistency notably in total number of occurrences, intraseasonal and multiple-year variations, snow spatial coverage, and the associated circulation patterns. Possible future change in extreme snow events was also explored utilizing the HiRAM RCP8.5 (2075–2100) simulation. The analyses suggest that a warming global climate tends to decrease the extreme snowfall events but increase extreme rainfall events.

1. Introduction

In the past few decades, the northeast United States (NEUS) experienced many catastrophic extreme winter snowstorms (Changnon and Changnon

2005; www.ncdc.noaa.gov/snow-and-ice/rsi/nesis) with the majority closely associated with extratropical cyclones (Agel et al. 2015). For example, the 8–9 February 2013 extratropical cyclone produced extremely heavy snow of 0.3–0.6 m across New York City and Long Island, and over 0.9 m in central Connecticut; a federal disaster was declared for Long Island and Connecticut (Ganetis and Colle 2015). Given the large population and economy of mega cities (such as Boston, New York City, Philadelphia, and Washington D.C.) along the NEUS coast [the Interstate 95 (I-95) corridor], it is imperative to better understand the dynamics and thermodynamics of extreme snowstorms and their possible future changes.

Many observational studies have been conducted to investigate the characteristics of extreme snowstorms.

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The location and intensity of jet streams play important roles (e.g., Kocin and Uccellini 2004a; Notaro et al. 2006; Colle et al. 2015). For example, Uccellini and Kocin (1987) illustrated the coupling of transverse circulations associated with two separate jet streak/trough systems that favors cyclogenesis and the development of severe winter weather conditions: a direct circulation located within the confluent entrance region of an upper-level jet streak over the NEUS or southeastern Canada, and an indirect circulation in the diffluent exit region of a jet streak associated with a trough near the East Coast. Grumm and Hart (2001) and Stuart and Grumm (2006) further suggested that the easterly wind anomalies in the upper and lower troposphere are common features of many record snowstorms. While the former anomalies (westerlies slower than normal) slow the movement of the system to prolong the event lifetime, the latter enhance low-level forcing and frontogenesis. In addition, the pathways of storm tracks have significant effects on the strength and spatial distribution of snowfall. The most common direction of cyclone tracks associated with large snowstorms was southwest to northeast, and the average orthogonal distance from the storm track to the heavy snow region was about 200 km (Changnon et al. 2008). Other factors such as temperature at 850 hPa (Browne and Younkin 1970; Kocin and Uccellini 1990) and large-scale teleconnections such as the Pacific–North American pattern (PNA) and the NAO (Notaro et al. 2006; Brown et al. 2010; Ning and Bradley 2015) also play certain roles in forming extreme snowstorms over the NEUS.

General circulation models (GCMs) are useful tools for providing insights into the interplay of dynamic and thermodynamic processes of extreme snowfall events and certainly are needed for projecting their future changes. In recent years, GCM simulations with high resolution have become readily available (e.g., Kitoh and Endo 2016; Mizuta et al. 2012, 2017). Specifically, the High Resolution Atmospheric Model (HiRAM) developed by Geophysical Fluid Dynamics Laboratory (GFDL) has demonstrated comparable performances with other widely used high-resolution AGCMs, such as the Hadley Centre Global Environment Model version 3–global climate version 2 (HadGEM3-GC2; Williams et al. 2015) and the MRI-AGCM3.2 (20 km; developed jointly by the Meteorological Research Institute and the Japan Meteorological Agency; Mizuta et al. 2012). The HIRAM can realistically simulate tropical cyclones (Zhao et al. 2009; Chen and Lin 2011, 2013; Tsou et al. 2016), extreme precipitation (Freychet et al. 2017a), extratropical disturbances (Chen et al. 2019), and snowfall (Freychet et al. 2017b) in aspects of both the historical climatology and the responses to future global

warming. In addition, the HIRAM outputs have been used to drive regional climate models by dynamical downscaling (Huang et al. 2016a,b, 2019) in both current and future climate conditions.

This study has two objectives. The first is to examine the observed characteristics of extreme snowstorm events along the NEUS coast, focusing on the occurrence statistics and the circulation; and the second is to study the HIRAM capability in simulating these characteristics. The rest of this paper is organized as follows: section 2 describes data and methods; sections 3 and 4 present, respectively, analyses of the occurrence of extreme snow events and the associated circulations; conclusions and discussion are given in section 5.

2. Data and analysis methodology

This section describes the observation data and the HIRAM simulations used to conduct comparative analyses.

a. Observations

The observed snowfall data were taken from the Global Historical Climatology Network (GHCN) dataset (Menne et al. 2012a,b), which provides station-based daily climate data over global land area. Considering many stations have missing or questionable snowfall records during 1980–2015, we only include stations where the total length of snowfall records is longer than 10 years (120 months) although the records are not necessarily continuous. This objective screening still yields, as shown in Fig. 1a, several hundreds of stations located over the NEUS. For the circulation, the ERA-Interim reanalysis (<https://rda.ucar.edu/datasets/ds627.0/>) with a horizontal resolution of 0.703° longitude $\times$ 0.703° latitude and vertically 36 pressure levels (Dee et al. 2011) is used.

b. HIRAM simulations

Two HIRAM simulations were used in this study: one historical run (1979–2015) and one future run (2075–2100). Both runs were conducted by and archived at the Research Center for Environmental Change (RCEC), Academia Sinica (Taiwan). While more details on the model setup and the simulation configuration are available in Zhao et al. (2009), Chen and Lin (2011), and Tsou et al. (2016), a brief description is given below.

The HIRAM, originally developed by GFDL, utilizes a hydrostatic finite-volume dynamic core in a cubed-sphere grid topology (Putman and Lin 2007) and is flexible in resolution. Specifically, the moist convective process is parameterized using a simplified scheme

FIG. 1. GHCN stations and HiRAM grids used for statistical analyses over four cities in the northeast United States: (a) spatial distribution and (b) number of GHCN stations that reported snowfall in each city during the cool season (November–March) of 1980–2015. All stations have snow reports for at least 10 years (120 months) within the 36 years; only stations (blue dots) and inland grids (red plus signs) within 50 km (boundaries indicated by circles) from the city centers were included in snowfall analyses for respective cities. There are 796 stations inside the domain (37° – 44° N; 79° – 50° W).

based on the shallow convection scheme by Bretherton et al. (2004), and the large-scale (stratiform) cloudiness is parameterized using a simple diagnostic scheme that assumes a subgrid-scale distribution of total water (Zhao et al. 2009). These configurations encourage the explicit convection to substantially contribute to the vertical transport of moisture and energy in the tropics while limiting the parameterized convection. Consequently, the parameterized convection works to help resolve the subgrid convection rather than supplant it entirely. We noticed that the simulated convection precipitation in winter over the NEUS is insignificant as compared to the large-scale precipitation. This is consistent with the fact that convection over the middle latitudes is very weak in winter and most precipitation is associated with large-scale air motions.

The historical and future simulations were both conducted using a C384 grid (horizontal resolution of about

25 km) and 32 vertical levels with the model top at 10 hPa. Prescribed monthly SST and sea ice concentration (SIC) were used to drive the high-resolution atmospheric model. For the historical simulation, the SST and SIC were from Hadley Center HadISST1 dataset ($1^{\circ} \times 1^{\circ}$; Rayner et al. 2003). For the future simulation, a pseudo global warming approach was adopted following Kusunoki (2018), where the SST and SIC were composited by superposing three parts: 1) the detrended interannual anomalies during 1979–2004 from the observation, 2) the linear trend during 2075–2100 from RCP8.5 projected by 28 CMIP5 models, 3) and the future change of 2075–2100 versus 1979–2004 projected by the multimodel ensemble.

Our analyses were mainly focused on the historical simulation for the purpose of evaluating the model performance in simulating the characteristics of observed extreme snowfall events, but a brief discussion addressing the effect of global warming on extreme snow events using the future simulation is given in section 5. All analyses of HiRAM simulations were conducted on the continuous cool seasons (November–March): 35 winters during 1980–2015 and 25 winters during 2075–2100.

c. Identification of extreme snowfall events

Three factors were considered in the identification of extreme snow events. First, because the extreme snowfall over the NEUS mostly occurs on a single day embedded in 2–5-day events (Agel et al. 2015), for simplicity we defined an extreme event as the single day with extreme snowfall. Second, regions with larger populations are usually more susceptible to heavy snowfall (Kocin and Uccellini 2004b), so we defined the extreme snow events based on snowfall data over four mega-cities along the I-95 corridor: Boston, New York City (NYC), Philadelphia, and Washington, D.C. Third, an extreme snowstorm should produce heavy snowfall over a large area rather than over only a specific single station (in the observation) or grid (in the simulation), so data from all GHCN stations (and HiRAM continental grids) that are less than 50 km (circles in Fig. 1a) from the city centers were included in the analyses. The number of stations and grids included for each city is given in Table 1. Note that the number of stations is 2–3 times the number of grids so that the effect of snow record gaps in many stations is small. As shown in Fig. 1b, the number of stations for the four cities with valid snowfall records fluctuates significantly; nevertheless, the numbers of valid stations, 10–20, are comparable with the numbers of HiRAM grids. The 50-km radius was chosen based on sensitivity tests of extreme snow events to other choices.

TABLE 1. Comparisons in snowfall statistics of four cities between the GHCN station observation (before the slash) and the HiRAM historical simulation (after the slash). Only GHCN stations and HiRAM inland grids within 50 km from the city centers were included in analyses. Note that the observed and simulated snowfall amounts are in different metrics: snowfall depth for GHCN and snow-equivalent-water amount for HiRAM. Days with snowfall larger than 1 mm in GHCN or snow-equivalent-water more than 0.1 mm in HiRAM were considered as snow days; the 95th percentile of snowfall amount at each city was separately calculated for GHCN and HiRAM with respect to snow days during 1980–2015; days with snowfall exceeding the 95th percentile of daily snowfall amount were considered as extreme snow days.

City	Station/grid count	Snow day count	95th percentile (mm)	Extreme snow day count
Boston, MA	26/13	1375/1206	137/18.6	69/61
NYC, NY	32/12	787/958	118/17.5	40/48
Philadelphia, PA	30/13	712/767	105/16.9	36/39
Washington, D.C.	34/15	595/605	111/19.2	30/31
Total	122/53	1755/1614	—	110/105

The procedure of identifying extreme snow events is as follows: first, for each of the four cities, the time series of daily-mean snowfall during the 35 cool seasons was calculated with data from selected stations (grids), and the 95th percentile of snowfall amount was calculated with respect to snow days; all days with at least one city having snowfall exceeding the local thresholds were considered as extreme snow days.

d. Composite circulation

It is worth first emphasizing that, for at least two reasons, the simulated weather events should not be expected to match either day by day or case by case with those from the observational reanalysis. First, some fluctuations crucial to the weather migration were not well accounted for in the model setup; for example, the day-by-day variation of SST was excluded by the prescribed monthly data. Second, for the long model simulation, the accumulated noises and biases could be large. Even if the extreme snowfall events between the simulation and observation coincide, the two events are not necessarily comparable. To ease the incompatibility, we categorized the identified extreme snow events into different types using the *K*-means cluster method, and then compared composite circulations of individual types between the simulation and observation.

The *K*-means cluster method has been widely applied to categorize circulation in climate studies (e.g., Michelangeli et al. 1995; Plaut et al. 2001; Moron et al. 2008, 2010; Roller et al. 2016; Agel et al. 2018, 2019). It classifies data into a predetermined number of clusters, where each sample belongs to the cluster whose center has the shortest distance to the sample. In this study, we utilize the off-the-shelf *K*-means codes provided in the Python Scikit-learn software package (Pedregosa et al. 2011).

Given the importance of both upper- and lower-level circulations to extreme snowstorms as revealed by

previous studies (e.g., Uccellini and Kocin 1987; Stuart and Grumm 2006), circulations at 200 and 850 hPa were classified using the multivariate *K*-means method based on the geopotential height fields. The geopotential height was considered because it can mostly determine the circulation, especially for the upper-level circulation, by reason of the geostrophic balance. The chosen domain is 30°–50°N, 90°–55°W, which centered over the NEUS and covered 1400 ERA grids in total (larger domains were also tested, with details given in the online supplemental material). The procedure is as follows: First, daily-mean circulations accompanied with extreme snow events were calculated for the observation and simulation data, and the simulation data were interpolated to the ERA grid. Second, the regional mean over the domain was subtracted at each surface of both datasets, because the circulation is determined by the geopotential gradient rather than the absolute geopotential height. Third, the observed circulations at the two levels were standardized temporally and classified into several clusters based on the Euclidean distance, and the simulated circulations were temporally standardized using statistics of observed circulations and sorted into observed clusters whose cluster centers had the shortest Euclidean distances to them, which ensured circulation classification of two datasets in the same framework. Finally, composite circulations were respectively calculated for the observation and simulation data by averaging all events belonging to individual clusters for comparative analyses.

We also tried clustering circulations at 200 and 850 hPa separately, which was expected to better resolve the variability of vertical structure/coupling of circulations. Major circulation types from this approach are comparable to circulation types from the multivariate clustering given below, but some spurious regimes that are scarce in the observation and/or the simulation are introduced. Therefore, results of this approach are not given in the main text, and interested

readers are referred to the online supplemental material for details.

3. Occurrence of extreme snowstorms

Table 1 shows the snowfall statistics of the four cities from both the GHCN observation and the HiRAM historical simulation. Note that because of their different metrics used to gauge snowfall amount in these two datasets, the snow days were defined in GHCN as days with daily snowfall greater than 1 mm and in HiRAM daily snow-equivalent-water exceeding 0.1 mm. In the observation, as expected, the number of (extreme) snow days decreases from north to south, with the number of snow days in Boston being nearly twice those in the other three cities. It is interesting that the 95th percentile is the smallest in Philadelphia (105 mm) with larger values in NYC (118 mm), Boston (137 mm), and Washington, D.C. (111 mm), implying that Washington, D.C. tends to have fewer but stronger snowstorms than the other cities. By contrast, the HiRAM simulation exhibits quite similar statistics in both the number of (extreme) snow days and the meridional variations of the number of snow days and the 95th percentile. However, it is clear that the number of (extreme) snow days in HiRAM is smaller in Boston but larger in the other cities as compared to the observations. We did several sensitivity tests by varying the lower limits for defining snow days in the observation and simulation data, and all tests lead to the same conclusion that the model relatively underestimates the number of snow days over Boston but overestimates those over the other cities, suggesting that the simulated snowfall is generally shifted southward compared with the observation. Nevertheless, both the observation and simulation indicate that Boston stands out as having different characteristics of snowfall occurrence than the other cities.

Next, we used the identified extreme events to study their characteristics including the event spatial coverage (i.e., the number of affected cities) and their interannual and intraseasonal variations. Figure 2 gives the occurrence frequency of single- and multicity extreme snow events. The Boston-only events, whose frequency is measured with a separate scale reference, count the most, having 52 of 110 in GHCN but fewer, 36 of 105, in HiRAM. For other types of single-city events, the model simulates larger occurrence frequency than the observation. For two-city events, the model generally overestimates (underestimates) the number of those affecting Boston (southern cities), and has one type (ND) that did not occur in the observation. For three-city events, results are comparable between two datasets; for four-city events, the model also has more

FIG. 2. Occurrence frequency of all possible single- and multicity extreme snow events in the GHCN (narrow bars) and the HiRAM historical simulation (wide bars). Labels of the bottom axis indicate cities that experienced extreme snowfall, with B, N, P, and D denoting Boston, NYC, Philadelphia, and Washington, respectively. The Boston-only (B) events are too frequent compared with other types of events, so their frequencies are plotted with different scale references (i.e., two y axes). The colors here and in Fig. 3 represent circulation types categorized using the *K*-means cluster method (detailed in section 4).

events. Therefore, despite the fact that the two datasets have similar numbers of extreme snowfall events for each city (Table 1), there are marked differences in the spatial coverage statistics, which are related to differences in circulation between the simulation and observation as will be shown below. Clearly, Boston is dominated by single-city events in both the observation (52 out of 65) and simulation (36 out of 61) while the other cities are mainly affected by multiple-city events, implying that the event circulations affecting Boston could be much different from those affecting the other cities.

The simulated interannual variation of extreme event occurrence is found to be consistent with observations in the multiyear scale, but not in the year-by-year scale (figure not shown). In the observation, extreme events present coherent interannual variation in the four cities: the occurrence frequency is higher around 1980–83, 1992–95, 2002–05, and 2008–10 and lower around 1986–90 and 1996–2000. The HiRAM simulation seems to well capture this observed variation. However, when examining individual years, the model biases are large. The correlation coefficients between interannual variations of the two datasets are very small, or even negative, for all cities (not shown here).

Figure 3 compares the extreme occurrence for the individual winter months. In the observation, for Boston the frequency is large throughout December–March, but for other cities it increases gradually from November to February and decreases afterward. In comparison, the simulated frequency in the four cities shows the same temporal variation (i.e., increasing from November to February and decreasing afterward). The model

FIG. 3. Comparisons of intraseasonal variation of extreme snowfall days between GHCN dataset (narrow bars) and HiRAM historical simulation (wide bars). The horizontal coordinate refers to November–March.

thus underestimates the frequency in December and January for Boston, but overestimates it in November for the other cities.

4. Circulation associated with extreme snow events

As mentioned in the introduction, atmospheric circulation, in particular at the upper and lower levels, exhibits certain anomalies related to extreme snowstorms. Here we used the cluster approach to study observed circulation patterns at 200 and 850 hPa during extreme snowfall events. After examining the total within-cluster variance and Caliński–Harabasz index (Caliński and Harabasz 1974) for various cluster numbers (details given in the online supplemental material), we conclude that three types can adequately provide the needed information. Below, the circulation types are presented and discussed using the three designations of A, B, and C.

a. Circulation clusters

Figure 4 presents composite circulations at 200 and 850 hPa for the observed extreme snow events. Clearly, the circulations differ mainly in the position and

strength of the jet stream at 200 hPa and the coupled low pressure system at 850 hPa. In type A, the jet stream is relatively strong, located at a high latitude along the path of the four cities, and coupled with an inland trough with four cities immersed in weak southerlies; in type B, the jet stream is slightly shifted southward, significantly weakened, and coupled with a closed cyclone at the coast that puts the four cities in quasi-calm conditions; and in type C, the jet stream is markedly shifted south of the four cities, significantly weakened, and coupled with a closed cyclone over the ocean close to the coast that yields northerlies across the NEUS. Note that these circulation types should be distinguished from those defined by Miller (1946), in which cyclones affecting the NEUS were classified based on the history of their genesis and development. Certainly, the two classifications are related in some way, but it is beyond the scope of the present study.

Two conditions favor the occurrence of extreme snow events for type A. First, although the trough at 850 hPa in type A is a weak system when compared with cyclones in type B and C, southerlies (though not strong) associated with the trough can provide a large amount of water vapor to the NEUS, especially in the southern

FIG. 4. Composite circulations associated with extreme snowfall in the observation, where three types (i.e., A, B, and C) are composited based on geopotential anomalies at 200 and 850 hPa. The purple lines represent contours of geopotential height that are plotted every 100 m at 200 hPa and every 20 m at 850 hPa, while the shadings indicate the U wind (m s^{-1}) at 200 hPa and the specific humidity at 850 hPa (g kg^{-1}). Black circles in this figure and Figs. 5–8 indicate the 50-km boundaries around centers of four cities. The composite specific humidity at 850 hPa at four cities from north to south is 1.6, 2.6, 3.0, and 3.5 g kg^{-1} in type A, 2.2, 2.7, 2.8, and 2.7 g kg^{-1} in type B, and 2.4, 2.3, 2.1, and 1.8 g kg^{-1} in type C. Numbers above each column give the occurrence frequency of individual circulation types in the ERA data (before the slash) and the HiRAM data (after the slash).

region (shaded in Figs. 4d–f), yielding heavy snowfall. Second, because the cities are located at the east of the inland trough in type A and the west of the ocean cyclone in type C, the large-scale rising motions at the cities in type A also tend to be stronger than those in type C (Fig. 8a vs Fig. 8g; Fig. 9a vs Fig. 9g).

It is noticed that composite circulations here bear both similarities to and differences from circulation patterns associated with total-precipitation extremes that were revealed by Agel et al. (2018, 2019). A weak jet stream situated to the south of the four cities at 200 hPa (i.e., type C) is favored in extremes of both snowfall and total precipitation. However, it is shown here that a strong jet stream situated to the north (i.e., type A) may also yield large number of extremes in snowfall (although perhaps weaker than those by type C) but not total precipitation. This is mostly because snow extremes here are defined quite differently than total-precipitation extremes in Agel et al. (2018, 2019) in several aspects such as concerned regions and periods, precipitation types, and threshold values. A snowfall extreme is not necessarily a total-precipitation extreme, and vice versa.

The composite spatial distributions of snowfall associated with the individual circulation types are given in

Fig. 5. In the observation, the snowfall is generally uniform over four cities in type A (Fig. 5a); as the jet stream becomes weaker in type B, the snowfall becomes heavier, especially for the northern NEUS coast (Fig. 5b); and when the jet stream is markedly weakened and shifted to the south in type C, the snowfall is significantly increased over northern cities and decreased over southern cities (Fig. 5c). This is consistent with the findings of Grumm and Hart (2001) and Stuart and Grumm (2006) that the slower westerlies in the upper levels favor heavier snowfall. As for the HiRAM simulation, the snowfall distribution presents similar patterns to the observation without regard to the different snowfall metrics for types B and C, and is relatively shifted southward for type A to some degree, which is in line with model biases in Boston as discussed above.

b. HiRAM circulation biases

The differences in circulation between the observation and simulation were analyzed by examining, for each type, the composite circulations and the occurrence frequency. The analyses indicate that circulations of the HiRAM simulated extreme snow events are quite close to those of the observed (not shown here). This is not surprising since the classification of simulated events

FIG. 5. Composite spatial distribution of snowfall/snow-equivalent-water (mm day^{-1}) associated with individual circulation types of extreme events in (a)–(c) the observation and (d)–(f) the HiRAM historical simulation. Numbers at lower-right corners give the occurrence frequencies of individual circulation types and their fractions (%) in the extreme snow events.

was calculated using clusters determined from observed events. Nevertheless, the results imply that the model captures well the major circulation characteristics associated with extreme snow events and variabilities within the individual types. However, biases exist and differ among the three types, as shown in Fig. 6. For types A and B, the geopotential heights at 200 hPa are relatively elevated in the northern part of the domain, while the geopotential heights at 850 hPa are relatively elevated in both the northern and eastern parts. This slows the jet stream at 200 hPa and causes a southwestward shift of the trough/cyclone at 850 hPa. This explains the less extreme snow events at Boston in the HiRAM simulation. For type C, the geopotential heights at 200 hPa are relatively elevated in the eastern part with the maximum elevation around 35°N, while the geopotential heights at 850 hPa are relatively elevated over the southeastern part (i.e., the ocean). This causes a northward shift of the jet stream at 200 hPa and a northwestward shift of the cyclone at 850 hPa.

Further analyses of the composite circulations near the surface and at 500 hPa are respectively given in Figs. 7 and 8. Near the surface (Fig. 7), the observation shows a closed cyclone in all circulation types, and the domain is warm in the southeast and cool in the northwest; all of these are well simulated in HiRAM. The

major bias manifests as the southwestward (northwestward) shift of the trough/cyclone in type A and B (type C), which is consistent with results of Fig. 6. In addition, the land–ocean thermal contrast is underestimated in A and B but overestimated in C. At 500 hPa (Fig. 8), the observed maximum updrafts are clearly stronger in C than in A and B, while updrafts over the four cities are weaker in the former than in the latter types as discussed above. By contrast, the simulated maximum updrafts are overestimated in A and B but underestimated in C, and updrafts over the four cities are mostly overestimated (especially for southern cities) because of the westward shift of the low pressure system.

For the vertical structure, Fig. 9 depicts composite circulations along the meridional cross section between 78° and 70°W. In the observation, the precipitation system (i.e., high relative humidity, indicated by shading) with the slow jet stream (B and C) reaches farther northward than that with the fast jet stream (A), consistent with snowfall distribution shown in Fig. 5. Both simulated dynamic and thermodynamic structures of the precipitation system are similar to the observations. The biases are mainly shown in the overestimations of both atmospheric instability (i.e., relative warmer in the lower troposphere and cooler in the upper troposphere) and updrafts.

FIG. 6. Differences of composite circulations associated with extreme snowfall between the HiRAM historical simulation and the observation (HiRAM minus ERA). Red (blue) contours indicate the positive (negative) anomalies of difference in geopotential height, where the regional-mean difference has been subtracted because the horizontal circulation is determined by the geopotential gradient rather than the absolute geopotential height; the hatching indicates regions where the difference of geopotential height is statistically significant (p value < 0.05); colored shadings indicate differences in the U wind (m s^{-1}) at 200 hPa and differences in the specific humidity (g kg^{-1}) at 850 hPa, respectively.

Despite the close agreement in circulation features between the observation and the HiRAM simulation, differences in the occurrence frequency of individual circulation types are remarkable. As shown in Figs. 4 and 5, the observed frequency of type A is close to that of type B; and the two are both higher than that of type C. By contrast, the simulation significantly underestimates frequencies of type A and C, but overestimates that of type B. Together with biases in composite circulations shown above, this implies that the model may have difficulties in simulating extreme cases of the jet stream (i.e., lacking in both extremely strong jet stream situated in the north and extremely weak jet stream situated in the south) and the coupled low pressure system.

For different cities, the dominating circulation could be different. Depicted in Fig. 2, the north-situated jet stream (A and B) can produce extreme snowfall of all possible coverages from single-city events to four-city events, while the south-situated jet stream (C) are mainly responsible for events affecting Boston (mostly Boston-only events). It is also evident that the underestimated occurrence frequency of types A and C is the major reason for the too few Boston-only extreme events in the HiRAM simulation. In addition, the intraseasonal variation of extreme events is dominated by events with the north-situated jet stream for all cities in

both the observation and the simulation; the simulation tends to have lower frequency of type A in all five months, higher frequency of type B in most months, and lower (higher) frequency of type C in December and January (February and March) than the observation (Fig. 3).

Note that the classification framework we used is to facilitate model–observation comparisons and cannot be used to differentiate extreme snowstorms from other events such as nonextreme snowstorms and rainstorms, or to identify extreme events in other simulations such as the HiRAM future simulation. In other words, the circulation characteristics obtained are necessary but not sufficient for the occurrence of extreme snowstorms. There are two major causes for this. First, large uncertainties exist in observations, for both snowfall and circulation data (e.g., few stations have snow reports that are continuous throughout the analysis period). This is an inherent problem for all observational datasets that is difficult to overcome. It causes biases to the identification of extreme events, masking or blurring key features that are only common to extreme events. Second, the current classification only includes dynamics and leaves out thermodynamics, which also play important roles in the evolution of snowstorms (e.g., the precipitation phases are closely related to temperature near the surface). As a result, characteristics of

FIG. 7. (left),(center) Composite circulations of individual types near the surface and (right) differences between ERA and HiRAM data. In the left and center columns, the purple lines represent contours of sea level pressure that are plotted every 4 hPa, while the shadings indicate 2-m air temperature ($^{\circ}\text{C}$) with the 0°C contours highlighted by orange lines. In the right column, red (blue) contours indicate positive (negative) anomalies of difference in sea level pressure, where the regional-mean difference has been subtracted; the hatching indicate regions where the difference of sea level pressure are statistically significant (p value < 0.05); colored shadings indicate the difference of 2-m air temperature.

composite circulations are not necessarily unique to snowstorms and may also be shared by rainstorms or mixed-phase storms.

5. Conclusions and discussion

This study examined observed characteristics of occurrence and circulation of extreme snowstorms affecting the NEUS coast during 1980–2015 and evaluated the HiRAM capabilities in simulating these characteristics, focusing on the I-95 corridor, where the mega-cities of Boston, New York City, Philadelphia, and Washington, D.C. are located. In the observation, the four cities southward from Boston experienced 69, 40, 36, and 30

extreme-snow days, respectively, determined by snowfall exceeding the local 95th percentile threshold of the daily snowfall amount (137, 118, 105, and 111 mm). By contrast, the HiRAM historical simulation has characteristics similar to those of the observations, notably the occurrence frequency, affected coverage, and multiple-year and intraseasonal variation of extreme events, but model biases also exist, highlighted by the slightly southward shifted of snow coverage. Applying the K -means cluster approach to the observed circulations at 200 and 850 hPa yields three types of composite circulations that differ among one another mainly in the strength and location of the jet stream at 200 hPa and the coupled low pressure system at 850 hPa: a strong and

FIG. 8. (left), (center) Composite circulations of individual types at 500 hPa and (right) differences between ERA and HiRAM data. In the left and center columns, the purple lines represent contours of geopotential heights that are plotted every 50 m, while the shadings indicate updraft velocity ($-\text{Pa s}^{-1}$). In the right column, red (blue) contours indicate positive (negative) anomalies of difference in geopotential height, where the regional-mean difference has been subtracted; the hatching indicates regions where the difference of geopotential height is statistically significant (p value < 0.05); colored shadings indicate the difference of updraft velocity.

north-situated jet stream overlying the four cities coupled with an inland trough, a weak and north-situated jet stream coupled with a closed cyclone at the coast, and a weak jet stream located to the south of the cities coupled with a closed cyclone over the ocean close to the coast. The model is capable of capturing these characteristics with minor deviations: a deceleration (northward shift) for the north-situated (south-situated) jet stream, a westward shift of the low pressure systems below, and an overestimation of the atmospheric instability and updrafts. Biases are also identified in the occurrence frequency of individual circulation types.

Since the HiRAM model exhibits strong capabilities in simulating extreme snowstorms affecting the NEUS,

the model projection on how climate changes may affect snowstorms in the future is of common interest. We compared the HiRAM historical and future simulations to get a glimpse of this aspect. Shown in Fig. 10, for each city and the entire region, the snow frequencies (gray parts of bars in Fig. 10a) decrease in the future by 70%–75% and the extreme snow frequencies (gray parts of bars in Fig. 10b) decrease even more significantly by 75%–85%. At the same time, however, it is noticed that extreme total-precipitation frequencies increase by 18%–63% (whole bars in Fig. 10b), although the total-precipitation frequencies (whole bars in Fig. 10a) tend to decrease by 10%–12%. This implies that some snow events may become rain events in the future as a result

FIG. 9. (left),(center) Composite circulations of individual types along the meridional cross section averaged over 78° – 70° W and (right) differences between ERA and HiRAM data. In left and center columns, the purple lines represent contours of equivalent potential temperature θ_e that are plotted every 5 K, while the shadings indicate relative humidity (%). In the right column, red (blue) contours indicate the positive (negative) difference of θ_e ; the hatching indicates regions where the difference of θ_e is statistically significant (p value < 0.05); colored shadings indicate the difference of relative humidity. The arrow above each column indicates the wind speed of 20 m s^{-1} for meridional wind or -0.2 Pa s^{-1} for updraft. Circles at the bottom of each plot indicate positions of the four cities.

of the temperature increase and other factors such as changes in circulations, moisture abundance, and atmospheric stability, of which more thorough studies of the mechanisms and processes are warranted.

Finally, it is noted that the track of an extreme low pressure system simulated by climate models, which plays a decisive role in the orientation of heavy precipitation and storm surge, is sensitive to horizontal resolutions. Colle et al. (2013) showed that climate models with a lower resolution tend to simulate more extratropical cyclones close to the NEUS coast than those with a higher resolution. Despite the fact that

HiRAM uses a resolution much higher than models in Colle et al. (2013), the tracks are still too close to the coast. This coupled with the findings that tropical cyclones over the western Pacific are too far from the land (Tsou et al. 2016) suggests that current GCMs may have inherent issues in simulating processes affecting locations of low pressure systems.

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FIG. 10. Mean annual frequency of snow (gray parts) and total precipitation (whole bars) events in winters of the historical simulation (1980–2015; narrow bars) and the future simulation (2075–2100; wide bars) by HiRAM. Days with snow-equivalent-water (total precipitation) greater than 0.1 mm were considered as snow (precipitation) events, of which those with snow-equivalent-water (total precipitation) exceeding the local 95th percentile threshold estimated from the historical simulation were considered as extreme snow (precipitation) events. The 95th percentile thresholds of total precipitation per day at the four cities are 26.9, 28.4, 27.7, and 26.4 mm, respectively.

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