11. WAS THE JANUARY 2016 MID-ATLANTIC SNOWSTORM "JONAS" SYMPTOMATIC OF CLIMATE CHANGE?

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Model simulations indicate that anthropogenic climate change has made extreme snowstorms less likely over the mid-Atlantic United States. Empirical evidence shows no decline since 1901, with recent storms colder than before.

Introduction. The biggest winter storm of 2016 named "Jonas"[1] over the eastern United States hit the mid-Atlantic states around 23 January, dumping up to 1 m of snow from Virginia to New York (Fig. 11.1a)[2], inflicting around $1 billion (U.S. dollars) in damages and causing 55 fatalities[3],[4].

This motivated our exploratory inquiry about how heavy winter precipitation events overall, and heavy snowstorms in particular, have changed in the mid-Atlantic region due to long-term climate change. In the eastern United States, heavy rain- and snowstorms have become more frequent during recent decades (Kunkel et al. 2013; Lawrimore et al. 2014). Both El Niño (Smith and O'Brien 2001; Lawrimore et al. 2014) and the negative phase of the NAO (Hoerling et al. 2010; Seager et al. 2010) increase the odds of heavy snow in this region. Given these natural drivers together with the regional rarity of major snowstorms (Changnon et al. 2006), identifying human-induced contributions requires model experimentation, results of which are presented here to augment empirical diagnosis of historical data.

Data and methods. A database of 987 climate stations (GHCN-D) of daily precipitation records since 1901 (Wolter et al. 2016) is used to identify heavy daily precipitation (≥25.4 mm). In the mid-Atlantic, 19 stations (Fig. 11.1b) have nearly complete records of precipitation, snowfall, and temperature during December–March 1900/01 through 2015/16. We define heavy daily snow (≥15.2 cm) in conjunction with heavy daily precipitation. Average temperatures during heavy precipitation days are used to derive an empirical relation of rain/snow transition thresholds for this region, inspired by Collins et al. (2004) and Kienzle (2008).

A 30-member ensemble of historical AMIP-style simulations is conducted with the T159 resolution (~85 km) ECHAM5 atmospheric model (Roeckner et al. 2003). This so-called "factual" simulation—using observed boundary and external radiative forcings—is compared to a parallel 30-member ensemble of "counterfactual" simulations. Linear trends of observed post-1880 sea surface temperatures (SST) are removed from the full time-varying SST; sea ice conditions are set to an early twentieth century climatology; and radiative forcings are altered to their 1880 values in counterfactual runs, thus retaining interannual and decadal variations of boundary forcings related to internal variability (Seager and Hoerling 2014; Sun et al. 2017, manuscript submitted to *Wea. Climate Extremes*). Simulated daily precipitation and temperature are analyzed for the mid-Atlantic domain of Fig. 11.1b. Heavy daily precipitation events are identified as in observations, and simulated snowstorms are inferred using the empirical relation of rain–snow temperature thresholds derived from observations. We compare factual versus counterfactual statistics of heavy precipitation and snowstorms for 2001–16 to maximize the climate change signal. A model's ability to simulate realistic storm tracks is an important attribute when considering heavy snowstorms. In this regard, we note

[1]http://nypost.com/2016/01/28/winter-storm-jonas-ranks-4th-worst-among-northeast-snowstorms/
[2]https://weather.com/storms/winter/news/winter-storm-jonas-record-snowstorm-new-york-city
[3]https://en.wikipedia.org/wiki/January_2016_United_States_blizzard
[4]www.washingtonpost.com/local/dc-politics/dcs-credit-card-was-shut-off-and-that-wasnt-the-worst-of-snowzilla-audit-finds/2017/01/11/5b84921a-d7f9-11e6-b8b2-cb5164beba6b_story.html?utm_term=.3c72de60003e&wpisrc=nl_localheads-draw6&wpmm=1

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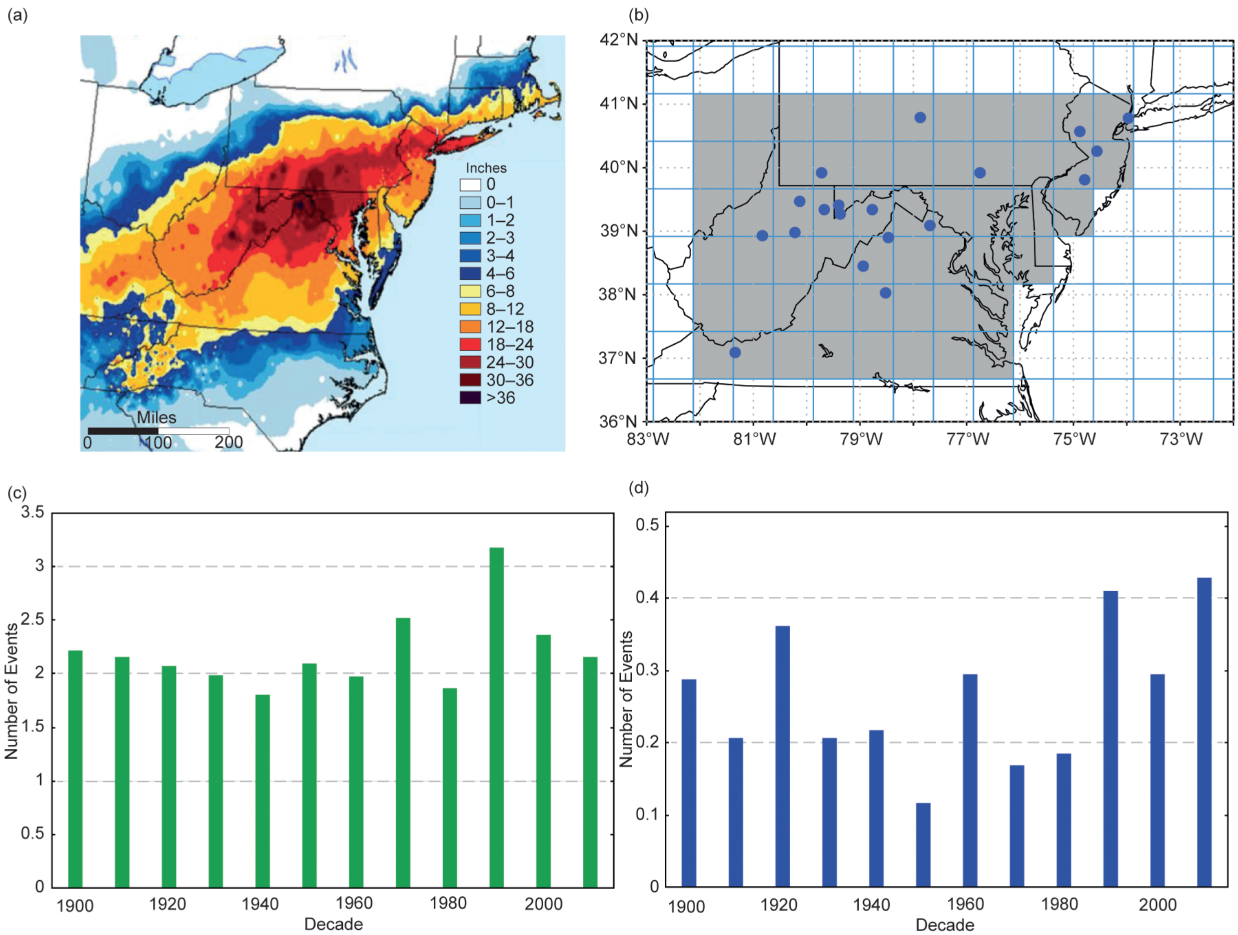

Fig. 11.1. (a) Jonas snowfall totals (inches); (b) 19 mid-Atlantic stations with 100yr+ precipitation records (Wolter et al. 2016) that also have more than 90% extant snowfall and temperature records during heavy precipitation days; gridding and shading refer to coverage by ECHAM5 for mid-Atlantic (~37°–41°N, ~74°–82°W); (c) Average annual counts of observed daily precipitation totals of 25.4 mm or higher from Dec–Mar 1900/01 through 2015/16 (last decade 2010/11 to 2015/16) for 19 mid-Atlantic stations; linear regression-based increase over 116 years: +20%; (d) As in (c) but for observed daily snowfall totals of 15.2 cm or higher (the number of usable stations varied from 16 to 19 per decade); linear regression-based increase over 116 years: +47%. [Source for (a): NWS Burlington.]

that storm tracks in the mid-Atlantic region are well represented in CMIP5 models with spatial resolution similar to that of our ECHAM5 experiments (Colle et al. 2015).

Results. (a) Empirical: Winter storm Jonas walloped our mid-Atlantic 19-station network: 12 stations reported daily totals of at least 23 cm of snow (25.4 mm of precipitation); see online supplement for more details.

Figure 11.1c documents the average number of heavy precipitation days per winter season and station on a decadal basis (overall average: 2.2). Figure 11.1d does the same for heavy snow days (average: 0.26). While both time series show an increase over the last 12 decades, their linear trends are not statistically significant due to large decadal variability. Nevertheless, our results for the mid-Atlantic corroborate upward trends in heavy snowstorms since 1901 in the Northeast (Kunkel et al. 2013).

When binned by daily average temperatures (Tave; Table 11.1), heavy precipitation events above +2°C contain little snow [snow-to-rain ratio (S/R) < 1], while those below −6°C guarantee heavy snow days (S/R > 8). We calculated heavy snow water equivalent (SWE; 15.2 mm) days based on assuming that no snow fell above +2°C, all snow below −6°C, and linear fractions in-between. This is similar to Collins et al. (2004) who inferred snowfall in the NCAR CAM3 model using 0°C and −5°C for their all-rain and all-snow thresholds. For the 19 mid-Atlantic stations, a total of 518 calculated heavy SWE days correspond well to 538 observed heavy snow days since 1901.

Table 11.1. Nineteen mid-Atlantic stations with more than 90% daily data for Dec–Mar 1900/01–2015/16, focusing on heavy daily precipitation events (25.4 mm+). "Tave" refers to daily average temperature bins (in 1°C steps between +6°C and −6°C); "#rain" refers to total number of rain-only events; "#snow" lists total number of heavy precipitation events with more than trace of snow; "%snow" gives percentage of the snowy days to total count [#snow*100/(#rain+#snow)]; "<S/R>" refers to total amount of snow divided by total amount of precipitation in each temperature bin; and "%6+:1" refers to percentage of snowy days with snow:rain ratio of 6:1 or higher. In each column, biggest values are highlighted in green, lowest in red.

Tave (°C)	#rain	#snow	%snow	<S/R>	%6+:1
≥6°C	1783	43	2.4%	0.05	0.1%
≥5/<6	372	33	8.1	0.17	0.7
≥4/<5	256	38	12.9	0.26	1.0
≥3/<4	324	67	17.1	0.36	1.5
≥2/<3	208	88	29.7	0.77	3.7
≥1/<2	203	127	38.5	1.21	5.8
≥0/<1	119	177	59.8	2.51	15.9
≥−1/<0	060	117	66.1	2.85	20.8
≥−2/<−1	036	173	82.8	4.06	30.6
≥−3/<−2	017	093	84.5	4.88	40.0
≥−4/<−3	018	094	83.9	5.48	45.6
≥−5/<−4	012	054	81.8	5.41	45.5
≥−6/<−5	005	031	86.1	7.28	61.1
<−6°C	003	117	97.5%	8.14	69.2%

Heavy snow counts show *no significant* change since 1901. Surprisingly, heavy snow days have become *significantly colder* (−2.55°C), in contrast with heavy rain-only days which have warmed slightly (+0.35°C; both in Fig. ES11.1).

(b) Model: Figure 11.2 shows results for the mid-Atlantic region from our model simulations. The Dec–Mar temperature difference between the factual and counterfactual experiments is +0.84°C (Fig. 11.2a) which is lower than the observed trend since 1900 (+1.1°C; Fig. ES11.2a). The corresponding precipitation difference for the same set of runs shows little change (+0.2%; Fig. 11.2b), compared to an observed decline of −4% (Fig. ES11.2b).

For each grid box and ensemble member, heavy precipitation events are extracted for Dec–Mar 2000/01 through 2015/16. Consistent with a wet bias of the model, the average number of such events is 3.7 per grid box in the factual case (Fig. 11.2c), *higher* than the observed frequency per climate station (2.3; Fig. 11.1c). Model snowstorms are derived by applying the same algorithm to calculate SWE as for observed data. The number of simulated heavy snow days is 0.17 cases per winter and grid box in the factual case (Fig. 11.2d), *lower* than observed (0.34; Fig. 11.1d).

Given the large model sample size, we find statistically significant changes in the frequency of heavy precipitation and snow days as a consequence of long-term climate change. An *increase* in the average number of heavy precipitation days of 7.0% is 99% significant for the means, but not for the full distribution [Fig. 11.2c; Komolgorov–Smirnov (K–S) value of 0.13]. A *decrease* by 17.5% for the average number of heavy snow days (Fig. 11.2d) is significant (*t*-test: 99%; K–S = 0.07). Comparing the number of events per winter in factual versus counterfactual climates indicates that 68.5% of the factual precipitation seasons exceed the counterfactual median (3.5 events per winter; Fig. 11.2c), a 37% increase in the relative risk of heavy precipitation events. By contrast, for heavy snowstorms, only 24.1% of the factual model seasons exceed the counterfactual median (0.2 events per winter; Fig. 11.2d), a 52% decrease in the relative risk of heavy snowstorms. Thus, the modeled likelihood of experiencing a heavy snowstorm has decreased in recent decades, as a result of climate change alone.

Comparing the probability distributions of both factual and counterfactual runs shows a wide spread in outcomes for heavy precipitation and snow events (Fig. 11.2c,d). This suggests low confidence in detecting the forced signal from a single sample of historical data. Concerning the model's forced signal,

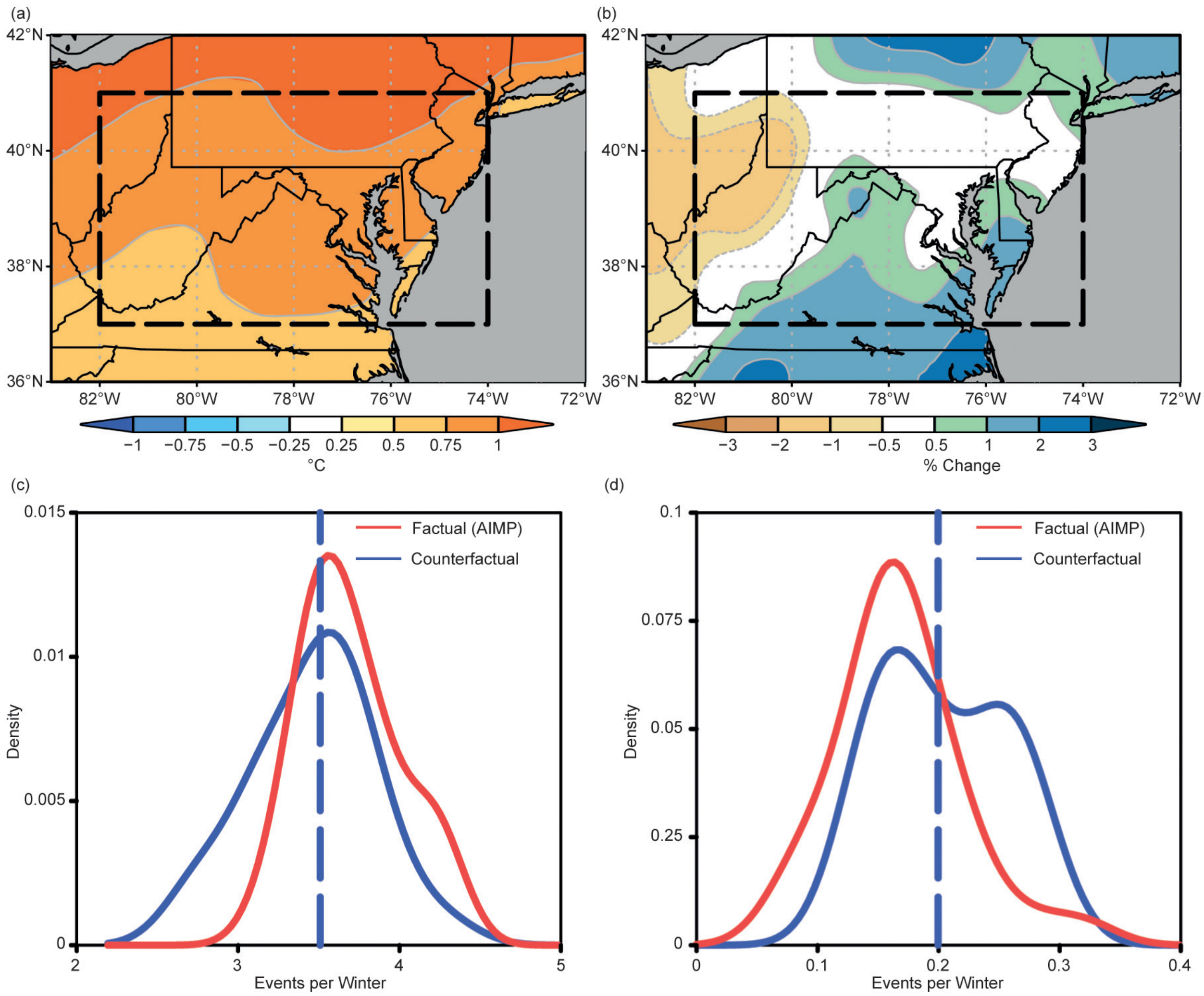

Fig. 11.2. ECHAM5 output for Dec–Mar 2000/01 through 2015/16. (a) Map of average change in seasonal temperatures (°C) of 30 factual runs compared to 30 counterfactual runs (+0.84°C) for mid-Atlantic (stippled outline); (b) As in (a) but for seasonal precipitation (+0.2%); (c) Probability distributions for mid-Atlantic region (57 grid boxes in Fig. 11.1b) for daily precipitation totals ≥ 25.4 mm, with median of 3.5 such events per season and grid box in counterfactual case (blue stippled vertical line); (d) As in (c) but for heavy snow events (SWE ≥ 15.2 mm), with median of 0.20 such events per counterfactual season and grid box. Probability distributions are nonparametric estimates of frequency distributions based on Kernel density and have been smoothed using Gaussian filter.

a key ingredient in its decrease of heavy snowstorms must be its increase in average temperature during modeled heavy precipitation days. More frequent heavy precipitation events alone—a plausible symptom of increased water vapor in a warmer climate (Hartmann et al. 2014)—would have implied more snowstorms. However, an increase in temperature more than countervailed the increase in moisture, yielding less heavy snowstorms.

Concluding remarks. Jonas was one of the most severe mid-Atlantic snowstorms of the last century (see http://nypost.com/2016/01/28/winter-storm-jonas-ranks-4th-worst-among-northeast-snowstorms/). We address how a class of such storms rather than Jonas itself are affected by anthropogenic climate change. Heavy snowstorm statistics derived from parallel climate experiments, one subjected to current climate conditions, the other subjected to conditions of the late nineteenth century, indicate a 52% decrease in the relative risk of experiencing a heavy snowstorm. Warmer temperatures dominated over the occurrence of more frequent heavy precipitation events in the model leading to fewer heavy snowstorms in the current climate. By contrast, the long-term observational record shows more heavy snowstorms in recent decades.

We reconcile these differences between the modeled and observed changes in heavy snowstorms by noting the large spread among the 30-members of ECHAM5 simulated mid-Atlantic snowstorm changes, implying low detectability of a change signal at this time. Heavy snowstorms are rare in the mid-Atlantic region, and their probability is affected by various natural drivers (El Niño, atmospheric blocking). Recent mid-Atlantic snowstorms were colder than those of the earlier twentieth century, contrary to a general winter warming trend in the region. It is plausible that internal variations in weather patterns responsible for mid-Atlantic snowstorms have dominated the observed increase. For instance, an eastward shift of storm tracks to slightly more offshore could cool the air mass during heavy precipitation events, allowing for heavy snow to fall over a wider reach of the mid-Atlantic (Changnon et al. 2008). In this regard, our results show a temperature increase of +0.3°C during model snowstorms, in contrast with the cooling trend in observed snowstorms since 1901 (−2.55°C), which may be due to natural decadal variations in storm tracks.

We further speculate that the wide observed range of temperatures during heavy snowstorms, many of them colder than −6°C, should allow for a continuation of at least some heavy snowstorm activity well into the future. This is consistent with O'Gorman's (2014) projection of only a slight decrease in the frequency of future extreme snowstorms compared to a much bigger decrease in seasonal snowfall totals for much of the northern midlatitudes. Meanwhile, the number of heavy mid-Atlantic snowstorms during the month of March has indeed declined compared to previous decades (Table ES11.1). Perhaps the future is showing its hand after all.

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