OCTOBER 2013 BLIZZARD IN WESTERN SOUTH DAKOTA

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Another important potential source of uncertainty is the adequacy of the control run variability, which is compared to "residual" observed variability in the Supplemental Material (Supplementary Figs. S6.5–7). Our basic findings appear robust to this uncertainty, although the simulation or estimate of internal climate variability remains an important topic for further research.

Discussion and conclusions. Three of the focus regions, northern tier—ANN, upper Midwest—MAM, and eastern United States—JJA, had record or near-record seasonal or annual precipitation anomalies during 2013 as well as detectable positive trends that were at least partly attributable to external forcing (anthropogenic and natural forcing combined). However, detection was marginal for the eastern United States. According to the models, external forcing increased the likelihood of rainfall events as extreme as the observed second-ranked year thresholds by factors of 1.6 to 2.5. The climate change detection here is only with respect to control run (intrinsic) climate variability. We have not attempted detection relative to natural forcing and intrinsic variability combined, since (a) the simulated ensemble-mean response to external forcings is generally much smaller than the observed long-term trends, interannual variability, and 2013 anomalies; and (b) too few simulations with only natural forcing were performed to sufficiently delineate the response to that forcing. Thus, while there is some suggestion of increased risk attributable to anthropogenic forcing in our findings (Supplementary Fig. S6.4), this is not emphasized here due to the lack of a sufficiently detectable long-term anthropogenic trend contribution. Extensions of the CMIP5 Natural Forcing runs through 2013, and larger ensembles of Natural Forcing experiments by various modeling centers, would be particularly useful for further investigations.

Important caveats are that we have not yet systematically analyzed regional precipitation trends globally (which would clarify the large-scale context of our findings), nor have we assessed possible data homogeneity issues, alternative datasets (e.g., Becker et al. 2013), or effects of radiative forcings on precipitation variance. Clearly, it would be much more difficult to detect anthropogenic influences on regional precipitation extremes than on surface temperatures (e.g., Knutson et al. 2013a). This is already evident in other recent analyses of regional precipitation trends (van Oldenborgh et al. 2013; Bhend and Whetton 2013). Nonetheless, some studies have reported detectable anthropogenic influence for zonal-mean precipitation (e.g., Zhang et al. 2007; Marvel and Bonfils 2013), precipitation extremes over large land regions of the Northern Hemisphere (Min et al. 2011), or precipitation changes in the extratropical Southern Hemisphere (Fyfe et al. 2012) or Mediterranean region (Hoerling et al. 2012). We conclude that the 2013 extreme precipitation "events" for three U.S. regions/seasons (northern tier—ANN, upper Midwest—MAM, and eastern United States—JJA) are tentatively attributable in part to external (anthropogenic and natural) forcing, with a likely much larger additional contribution from unforced intrinsic variability. We suggest that these regions be monitored for possible future emergence of anthropogenically forced precipitation increases, including more extreme seasonal or annual mean rainfall.

7. OCTOBER 2013 BLIZZARD IN WESTERN SOUTH DAKOTA

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An early October blizzard in South Dakota is determined to be climatologically anomalous. Climate models suggest that early autumn extreme snowfall events in western South Dakota are less likely due to anthropogenic climate change.

Introduction. An early season blizzard on 4–5 October 2013 in western South Dakota (SD) and neighboring areas of Wyoming, Nebraska, and North Dakota caused severe infrastructure damage and economic losses to businesses and agricultural communities. Estimated losses total $38 million in SD alone.

The blizzard produced 50.8–99.6 cm of snow across the plains and 139.7 cm of snow in the northern

Black Hills (Fig.7.1a). Rapid City, SD, measured 58.4 cm of snowfall during the storm, with 48.3 cm in a 24-hour period. This 24-hour record surpassed the 94-year-old October record by about 22.9 cm and fell just below the all-time 24-hour snowfall record of 50.8 cm set six months earlier on 9 April 2013.

Accumulated precipitation (rainfall plus liquid snowfall water equivalent, SWE) during 4–5 October amounted to as much as 17.1 cm at Lead, SD, with larger totals reported in unofficial observations. The storm total SWE amounted to about 20 percent of the annual average across the northern Black Hills and adjacent plains counties.

Outside of the Black Hills region, agriculture comprises the primary economy and livelihood in western SD. Initial damage assessments include approximately 45 000 livestock that perished in the storm, with 90% loss in some herds. The combination of antecedent soaking rain, large snowfall totals, and blizzard conditions resulted in animal deaths by hypothermia or suffocation due to wind-blown snow. The timing of the blizzard meant livestock were unprepared physiologically for the winter-like conditions and were vulnerable in open pastures. Despite advance notice of the impending storm, there was not sufficient time to move cattle to more sheltered areas. Municipal damage from the blizzard included downed trees and broken utility poles leading to long power outages in rural areas.

Blizzard reporting and recovery efforts were slowed by the unfortunate timing of the U.S. federal government shutdown 1–16 October 2013. Only critical offices were open, such as the National Weather Service, which issued a blizzard warning 15 hours prior to the onset of the event.

Historical context and synoptic setting. This event occurred in the western portion of the U.S. "blizzard alley" (Schwartz and Schmidlin 2002). A similar blizzard, centered in western North Dakota, occurred on 4–5 October 2005 (NCDC 2005; also see http://www.crh.noaa.gov/Image/bis/sd2005/October.pdf)—yielding two October blizzards for parts of the Dakotas just eight years apart. By comparison, only one-to-two October blizzards were reported per

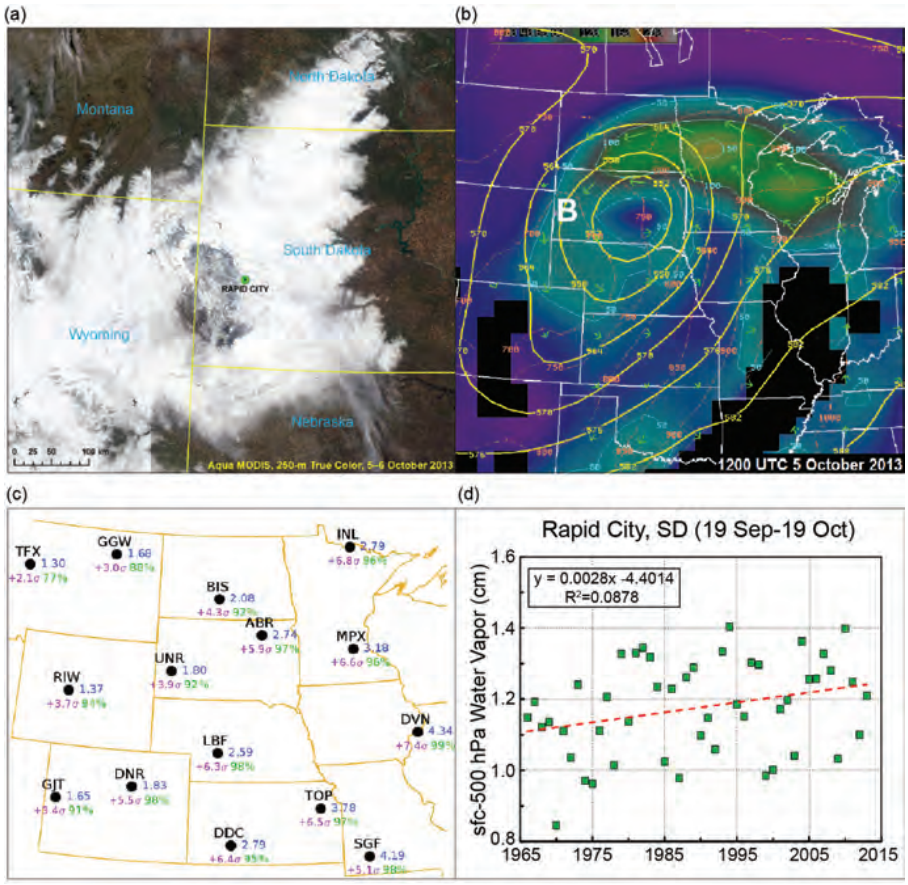

Fig. 7.1. (a) Aqua MODIS true-color 250-m resolution satellite depiction of snow cover centered on the South Dakota Black Hills for 5–6 October 2013 (http://ge.ssec.wisc.edu/modis-today/index.php). Two images were stitched together for 5 October (left) and 6 October (right) to avoid cloud contamination. (b) North American Mesoscale (NAM) model zero-hour forecast valid 1200 UTC 5 October 2013 for 500-hPa heights (six-dam yellow contours) and moisture transport vectors (green), moisture transport magnitude (g kg^{-1} m s^{-1}, shaded with legend at upper left), and pressure (50-hPa orange dashed contours) on the 295-K isentropic surface. The white "B" is centered on the Black Hills. (c) Maximum surface-to-300-hPa column water vapor (cm, blue) from 1200 UTC 3 October 2013 to 0000 UTC 6 October 2013. The corresponding percentiles (green) and standard deviations from the mean (purple) are based on the October observational period of record for each upper-air site (http://www.crh.noaa.gov/unr/?n=pw). (d) Average surface-to-500-hPa column water vapor per year for 19 September–19 October from 1966 to 2013 for Rapid City, SD. The linear trend (red dashed) illustrates an increase of 11.9% over 48 years.

county during 1959–99 (Schwartz and Schmidlin 2002), indicating the rarity of October blizzards. Furthermore, snowfall is rare in early autumn (19 September–19 October) across the plains, with only 48 days of measurable snowfall reported during early autumn in Rapid City in 63 years.

The October 2013 blizzard was produced by a strong low-pressure system similar to conditions identified in other heavy snowstorms (e.g., Graves et al. 2003; Jurewicz and Evans 2004; Novak et al. 2004; Moore et al. 2005), with mesoscale to synoptic-scale forcing for ascent aided by jet streak coupling (Uccellini and Kocin 1987), a trough of warm air aloft (trowal; Martin 1999), and low- to midlevel frontogenesis. The mature phase of the synoptic system featured 500-hPa heights of 547 dam over south-central SD (Fig. 7.1b), reaching standardized anomalies (σ) of –2.5 to –3.0. While these anomalies were significantly less than those associated with other blizzards in the region, they were comparable to 24 major snowstorms in Grumm and Hart (2001). These moderately strong anomalies suggest the storm system was intense, regardless of season, but not unprecedented in terms of 500-hPa heights.

By contrast, precipitable water (PW)—supported by the trowal—concurrent with the blizzard reached +2.1σ to +7.4σ across the broader region (Fig. 7.1c), reaching the 92nd to 99th percentile for October. The total storm precipitation ranks as a 1-in-10 event for any time of year (NOAA HDSC, http://hdsc.nws.noaa.gov/hdsc/pfds/pfds_map_cont.html?bkmrk=sd). The low-level winds transported this anomalously high water vapor into western SD (Fig. 7.1b). When compared to previous studies, these were highly anomalous water vapor values (e.g., Hart and Grumm 2001; Junker et al. 2008; Mayes et al. 2009; Graham and Grumm 2010), with return periods ranging from 30 days (+4σ) to 10 years (+7σ).

Rapid City upper-air soundings for 19 September–19 October from 1966 to 2013 showed an 11.9% increase in water vapor ($\rho = 0.30$, Fig. 7.1d), which is not significant at $\alpha = 0.05$ for the Mann–Kendall test. No trend was found in the number of days with PW above the 95th and 99th percentiles. Thus, we cannot conclude, based on this limited observational dataset, whether the probability of extreme atmospheric water vapor has changed for the Black Hills region.

Role of Anthropogenic Climate Change. We considered the likelihood of such events under the modern climate compared to pre-industrial conditions free of anthropogenic influence using a model ensemble approach.

Data and methods. Daily precipitation rate and maximum and minimum temperature were acquired from eight models participating in the Coupled Model Intercomparison Project Phase 5 (CMIP5) experiments: CCSM4, NorESM1M, CanESM2, CNRM-CM5, CSIRO-MK3-6-0, GFDL-ESM2G, MIROC5, and INMCM4 (Supplementary Table S7.1). PW data for the first four of these models also were acquired. These models were chosen based on overall performance in simulating the climate of North America (Sheffield et al. 2013) and disparate model genealogies (Knutti and Sedláček 2013). Model data were taken from both preindustrial control runs (PI) and from "modern day" runs (MD) encompassing 2013 (2000–29) using historical 20th century runs ending in 2005 and extending these through 2029 using output from the Representative Concentration Pathway 8.5 (RCP85). Over 100 years of daily temperature and precipitation for PI runs were used for the primary analysis of estimating snowfall extremes. Model simulated snowfall flux was not used given potential biases in the joint distribution of simulated precipitation and temperature. Rather, intramodel biases in daily precipitation and temperature were bias-corrected using empirical equidistant quantile mapping (Li et al. 2010a) extended to two dimensions to fit the distribution of daily observations from ERA-Interim reanalysis (Dee et al. 2011). Model output was bias corrected using the common period from 1979–2012 while allowing for differences in the empirical distribution for PI and MD runs post 2012. Daily SWE was estimated using the empirical precipitation phase transformation of Dai (2008).

PW was calculated by vertically integrating specific humidity on isobaric surfaces. Unfortunately, most CMIP5 PI runs only archived ~20 years of pressure-level variables at the daily time resolution, thereby limiting a thorough analysis of PW. Instead, projected changes in PW are provided as a supplement to the main analysis.

Three metrics of SWE were considered for the period 19 September–19 October for both PI and MD experiments: (a) annual maxima daily SWE, (b) 90th percentile of annual maxima daily SWE, and (c) average SWE. Statistical significance was assessed by bootstrap resampling with replacement, using 1000 30-year samples from the PI runs. Differences were noted as significant when MD values fall outside the 95% confidence interval of the PI sample.

Results. Differences between the maximum series of daily SWE for early autumn showed a consistent

shift towards a reduction in the magnitude of extremes in MD runs with a multimodel mean decrease of around one-third (Fig. 7.2). Likewise, while two models showed a nonsignificant increase for a 90th percentile early autumn maximum daily SWE, the MD runs primarily tended toward reduced magnitude (mean decrease of 20%) relative to PI runs. However, the changes for both metrics were only significant for a single model and were not considered a robust change. These results largely mirrored projected changes in early autumn SWE that showed intermodel agreement of reduced SWE relative to PI runs (mean decrease of 35%). By contrast, simulated differences in early autumn maximum daily precipitation and the 90th percentile early autumn daily precipitation showed nominal and mixed changes. Increased PW in MD runs relative to PI was found consistently across the study area and was consistent with overall increases in temperature and potential water holding capacity scaling with the Clausius–Clapeyron relationship.

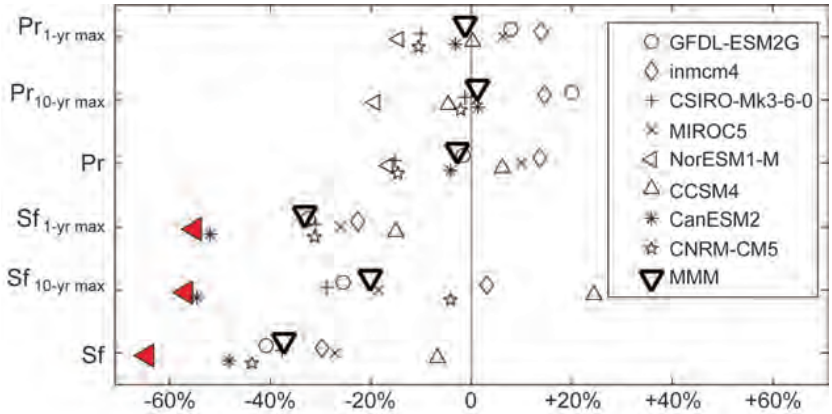

Fig. 7.2. Intramodel differences in the percent change in precipitation (Pr) and snowfall (Sf) between MD and PI in western South Dakota over a 30-day period centered on October 4. Differences are shown for annual extreme (1-yr max), 1-in-10 year annual extreme (10-yr max), and overall means. Statistically significant differences are denoted by red triangles; open triangles denote the eight-model average. A list of the models used is provided in Supplementary Table S7.1. Increased PW in MD runs relative to PI was found consistently across the study area and was consistent with overall increases in temperature and potential water holding capacity scaling with the Clausius–Clapeyron relationship. These findings also held for differences in early autumn maximum series of PW, with a multimodel increase of around 7% for the study area (not shown).

Conclusions. The record-setting early season blizzard of October 2013 had significant impact on the agriculture, infrastructure, and economy of western SD. This event was associated with highly anomalous (95th to 99th percentile) atmospheric water vapor for early autumn and anomalous, but not unprecedented, 500-hPa heights for any time of year.

While several climate models are consistent with the observations in showing an increase in PW, there is no apparent model agreement regarding changes in extreme precipitation or snowfall in the early autumn season for western SD under modern conditions relative to preindustrial conditions.

8. MULTIMODEL ASSESSMENT OF EXTREME ANNUAL-MEAN WARM ANOMALIES DURING 2013 OVER REGIONS OF AUSTRALIA AND THE WESTERN TROPICAL PACIFIC

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CMIP5 simulations suggest that the extremely warm year observed over Australia and the far western Pacific during 2013 was largely attributable to human forcing of the climate system.

Introduction. A global survey of surface temperature anomalies occurring during 2013 (Fig. 8.1a; Supplementary Fig. S8.1) in the HadCRUT4 observations (Morice et al. 2012) reveals pronounced warm an-