AGU100 ADVANCING EARTH AND SPACE SCIENCE

Geophysical Research Letters

RESEARCH LETTER
10.1029/2018GL077069

Key Points:
- Less storm days and hail days have been observed in the Tibetan Plateau since 1960s and 1980s
- Weaker atmospheric instability associated with drier midtroposphere led to the reduction of severe storm
- The changes of melting level height and vertical wind shear play critical roles in the change of hail occurrence

Correspondence to:
Q. Zhang and W. Li,
qzhang@pku.edu.cn;
wenhong.li@duke.edu

Citation:
Zou, T., Zhang, Q., Li, W., & Li, J. (2018). Responses of hail and storm days to climate change in the Tibetan Plateau. *Geophysical Research Letters*, *45*. https://doi.org/10.1029/2018GL077069

Received 9 JAN 2018
Accepted 24 APR 2018
Accepted article online 30 APR 2018

Responses of Hail and Storm Days to Climate Change in the Tibetan Plateau

Tian Zou[1,2], Qinghong Zhang[1], Wenhong Li[2], and Jihong Li[3]

[1]Department of Atmospheric and Oceanic Sciences, School of Physics, Peking University, Beijing, China, [2]Earth and Ocean Sciences, Nicholas School of the Environment, Duke University, Durham, NC, USA, [3]Tibet Nagqu Region Meteorological Bureau, Nagqu, China

Abstract There is increasing concern that local severe storm occurrence may be changing as a result of climate change. The Tibetan Plateau (TP), one of the world's most sensitive areas to climate change, became significantly warmer during recent decades. Since 1960 (1980), storm (hail) days have been decreasing by 6.2%/decade (18.3%/decade) in the region. However, what caused the frequency changes of storm and hail in the TP is largely unknown. Based on 53-year continuous weather records at 48 TP stations and reanalysis data, we show here for the first time that the consistent decline of storm days is strongly related to a drier midtroposphere since 1960. Further analysis demonstrated that fewer hail days are driven by an elevation of the melting level (thermodynamically) and a weaker wind shear (dynamically) in a warming climate. These results imply that less storm and hail may occur over TP when climate warms.

Plain Language Summary How the severe storm, such as hail and thunderstorm, will respond to climate change remains uncertain. Particularly, the Tibetan Plateau, which experienced greatest hail frequency and also has one of the most frequent occurrences of severe storms in China, has been found to be one of the most sensitive areas to global climate change. In this work, we tried to explain the connection between the change of severe storm and the change of climate in the Tibetan Plateau. To do this, we used continuous and persistent weather phenomena reports recorded by professionally well-trained observers over the Tibetan Plateau and analyzed storm-related parameters using both sounding data and reanalysis data over half a century. We demonstrated that there was consistent decline of severe storm which is strongly related to a drier midtroposphere. Further analysis demonstrated that recent years with less hail days present higher melting level and weaker wind shear than those years with more hail days. These results provide us a better understanding of the response of severe storm to climate change and imply that there would be much less severe storm if warming continues in the near future in the Tibetan Plateau.

1. Introduction

The impact of climate change on severe weather, which includes thunderstorms, hailstorms, and tornadoes (American Meteorological Society, 2017), is a persistent challenge for research, decision-making, and stakeholder communities (Mahoney et al., 2012). This is because their temporal and spatial scales are usually in the order of minutes to hours and hundreds of meters to hundreds of kilometers (Markowski & Richardson, 2010), respectively, while the corresponding scales for climate change could be years/decades and regional/global. Nevertheless, based on observation/modeling studies of severe storm, some of the environmental conditions conducive to storm occurrence have been summarized (Markowski & Richardson, 2010), which are concluded, but not limited to, strong instability, moisture at low level, high vertical wind speed, and large vertical wind shear. With different data sources for the long-term variation of severe storm, such as direct measurements from meteorological stations and indirect databases from insurance companies, trends of severe storm have been explored in China (Xie et al., 2008; Zhang et al., 2017), the United States (Changnon & Changnon, 2000; Doswell III et al., 2005), southeastern Australia (Niall & Walsh, 2005), Ontario, Canada (Cao, 2008), Argentina (Mezher et al., 2012), and Europe (Berthet et al., 2011; Kunz et al., 2009; Púčik et al., 2015; Tuovinen et al., 2009), separately. The meteorological conditions prevailing in the Tibetan Plateau (TP) have been studied in previous studies, but the TP has never been discussed as a unique region in view of its special geographical features. For example, in the study of Xie et al. (2008), the TP area was divided into two parts by the definition of the boundary of northern and southern China.

The TP is the highest plateau in the world and is also found to be one of the most sensitive areas to climate change (Liu & Chen, 2000). Compared to other regions in China, the TP experiences the most frequent

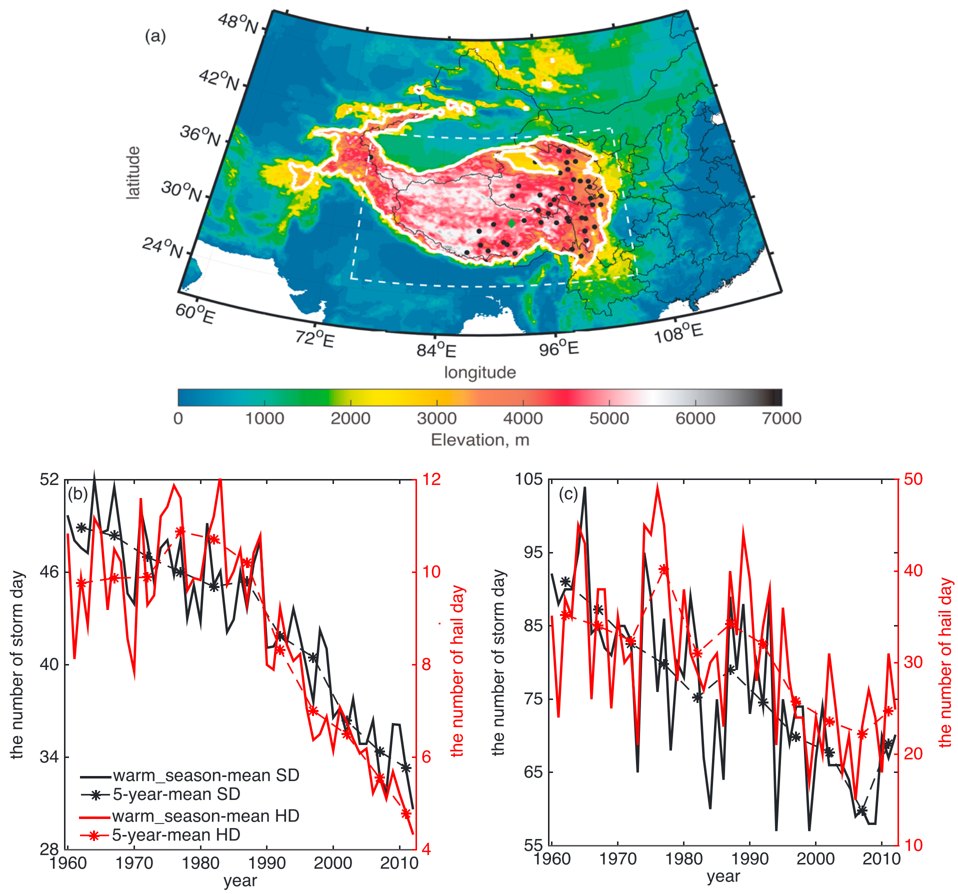

Figure 1. Station distribution in the Tibetan Plateau (TP) and the variations of storm day (SD) and hail day (HD). (a) Meteorological stations (black dots) within the study region (dashed box), and the white contour highlights the 3,000-m-elevation line. The green diamond indicates Nagqu station (31.29°N, 92.04°E). Time series of warm season mean HD (red lines) and SD (black lines), (b) averaged over TP, and (c) in Nagqu during 1960 to 2012. The dash lines present the 5-year average values.

occurrence of hail and thunderstorm (Zhang et al., 2017). As given by Liu and Chen (2000), significant surface warming in the TP has been observed since 1950s. Temperature increases at an average rate of 0.16 °C/decade over the TP during 1955–1996. Duan and Xiao (2015) confirmed that the rate of warming has accelerated to be about twice as fast as the global average after 1990s. Previous analysis (Li et al., 2016; Zhang et al., 2017) suggested that thunderstorms/hail in the TP have generally displayed a decreasing tendency in a warming climate. However, our results demonstrated that severe storm has occurred less since 1960, while the occurrence of hail remained constant from 1960 to 1980 and decreased afterward. The physical basis for such different trends of SD and HD has not been systematically investigated. Understanding the processes contributing to variations in occurrence of hail/severe storm and their environmental controls is important for accessing hail and severe storm threats and potentially mitigating hail damage and flood risk in a warmer climate.

This paper presents by far the most comprehensive analysis of SD and HD trends during 1960–2012 using continuous and coherent severe weather reports from 48 manned stations over TP (Figure 1a). We focus on the warm season, that is, from June to September, when most severe storm occurs (Zhang et al., 2008). Physical analyses are based on local sounding observations and a global reanalysis data set.

2. Data and Methods

The TP is defined as the area with elevation higher than 3,000 m within 25°–40°N, 75°–105°E (Figure 1). We first examined the frequency changes of severe storm and hail in the TP via weather phenomenon data sets. The weather phenomena, observed and recorded by well-trained, professional observers, include rain, snow, hail,[1] thunderstorms, lightning, squalls, high winds, and tornados. Then, the station with the most frequent occurrence of severe storm was selected to determine the preconditions for severe storm using radiosonde data. Related parameters were studied using National Centers for Environmental Prediction (NCEP) and National Center for Atmospheric Research (NCAR) reanalysis data (i.e., NCEP/NCAR Reanalysis-1), which produce similar trends to the sounding data.

2.1. Definition of a Storm Day and a Hail Day

Weather records were obtained from regularly manual observations collected by the National Meteorological Information Center of the China Meteorological Administration (NMIC-CMA). This database includes weather phenomena occurring on each day. A hail (storm) day for a station is defined as the day when hail (severe weather phenomenon, which may include hails, thunderstorms, and/or tornados) is recorded at that station.

2.2. Parameters Key to the Formation of Severe Storm in the TP

Many environmental parameters designed to identify occurrence of thunderstorms (John & Doswell III, 1992) are applicable to many places with the altitudes lower than 500 m, but some parameters may not be appropriate for the TP (mean altitude >3,000 m). Thus, modified parameters were employed in here.

1. The modified *K* index (MKI) is defined following You et al. (2012)

$$\mathrm{MKI} = (T_{500} - T_{300}) + T_{\mathrm{d}500} - (T - T_{\mathrm{d}})_{400} \tag{1}$$

where T and T_d denote temperature and dew point temperature, respectively, and the subscripts represent the pressure levels of the atmosphere in hPa. The parameter is derived from the *K* index (a measure of thunderstorm potential in meteorology) proposed by George (1960) but using T and T_d at higher levels. You et al. (2012) applied this modification first and demonstrated that MKI differs significantly for days with and without thunderstorms at several stations in the TP.

2. Precipitable water (PW) is defined as the total atmospheric water vapor contained in a vertical column of unit cross-sectional area extending between two layers. Because there is too much missing sounding data above 200 hPa, we selected the ground and 200 hPa as the bottom and top layers to make the integration when calculating PW based on the quality control criteria introduced in the following subsection.
3. Convective available potential energy (CAPE), a measure of convective energy and positive buoyancy of an air parcel, is calculated as in Williams and Renno (1993) but only integrated to 200 hPa.
4. Melting level height (MLH), a strong control of freeze-thaw processes (Diaz and Graham, 1996), is defined as the height at which air temperature falls below zero following recent studies (Dessens et al., 2015; Mahoney et al., 2012).
5. Vertical wind shear (VWS), a critical dynamic factor in the determination of thunderstorm type and potential storm severity (Weisman & Klemp, 1982) as well as convection initiation (Lee et al., 1991), is defined as the wind speed difference between the ground and 400 hPa in the TP.

2.3. Quality Control for Station Data Sets

For weather record data, where more than 5 days are missing in each warm season for each station, the year is considered invalid; and with one or more invalid years for a station, the station is considered invalid. The data among almost half of the stations are available after 1960, especially the stations located in the western TP. Data after 2012 were not used due to the change of observation since 2013 (communications with the NMIC-CMA); that is, the in situ measurements do not include thunderstorm phenomena record during the nighttime. Thus, 48 stations with consistent recordings from 1960 to 2012 (Figure 1) are used here.

Soundings are recorded twice daily (06:00 and 18:00 local solar time [LST], which is UTC + 6), and surface observations are made at 3-hr interval. The same QC rule as for weather phenomena is applied to each sounding variable. Because convection over TP occurs mostly in the afternoon (Xu & Zipser, 2011), the soundings at 06:00 LST were used to calculate the preconditions of severe storm. The parameters associated with the surface elements are modified to best capture the preconditions of severe storm (You et al., 2012). Surface T and T_d at 12:00 LST are used instead of those at 06:00 LST. We notice that the old version of the sounding equipment was replaced from 2000 in China (Tang et al., 2014), with the replacement occurring over TP at the end of 2004. This update may lead to discontinuous relative humidity. Therefore, we conduct analyses during the separate periods of 1960–2004 and 2005–2012.

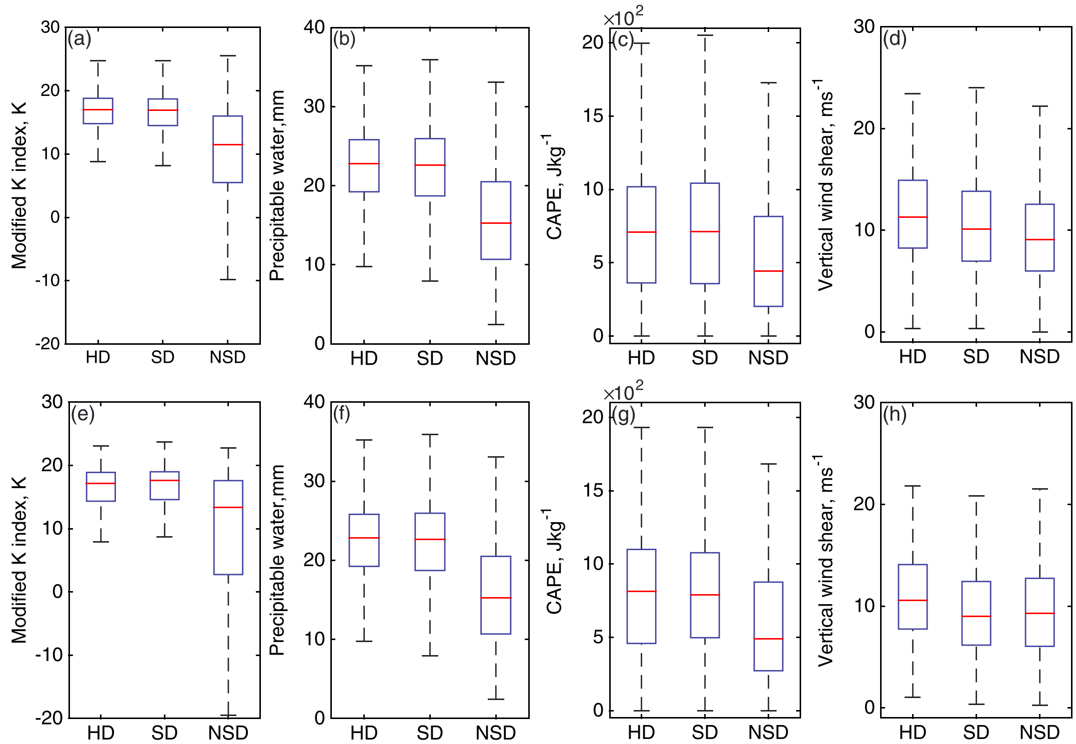

Figure 2. Box and whisker plots of modified *K* index (K), precipitable water (mm), convective available potential energy (J/kg), and vertical wind shear (m/s) (from left to right) on hail day, storm day, and no-storm day in Nagqu. The boxes denote 25th to 75th percentiles, with red horizontal bar at the median. The vertical dash lines (whiskers) extend to the 10th and 90th percentiles. (top row) Period 1960 to 2004. (bottom row) Period 2005 to 2012.

2.4. Analysis Methods

Composite analysis is used to detect if there are significant differences in MLH/VWS between the years with relatively high and low occurrences of HD. We choose the top 12.5% and the bottom 12.5% as the criteria to distinguish the top hail year (THY) and bottom hail year (BHY). These criteria are defined to acquire enough samples to conduct a composite analysis and obtain distribution statistics. We also check other criteria, such as the use of 15%, and obtain similar results.

To determine the trends of severe storm and environmental parameters, a nonparametric Mann-Kendall test (Kendall, 1955; Mann, 1945) is used. And a modified approach is applied, considering the impact of autocorrelation (Hamed & Rao, 1998) in the study.

3. Results

3.1. Changes of SDs and HDs During 1960–2012 Over TP

During the warm season, SDs and HDs (Figure 1b) averaged over the 48 stations had different trends in the last five decades. The variations of SD decrease continuously, with an averaged trend of −3.1 days/decade (significant at the 0.01 level). HD hardly changed before the 1970s and then increased slightly before declining significantly after the 1980s. The rate of increase before 1980 is 5.8%/decade for HD compared to −3.8%/decade for SD. During 1980–2012, the rates of decrease are −9.2%/decade for SD and 18.3%/decade for HD, both significant at the 0.01 level.

As shown here, the change of HD is not totally consistent with that of SD, which has decreased since 1960. To explain the physical reasons, we examined the variations of preconditions for severe storm at Nagqu whose trends of SD and HD are generally similar to those in the TP (Figure 1c). We first attempt to determine why there was a decreasing trend in SD during 1960–2012 (section 3.2) and then to explain the different variations of HD and SD (section 3.3).

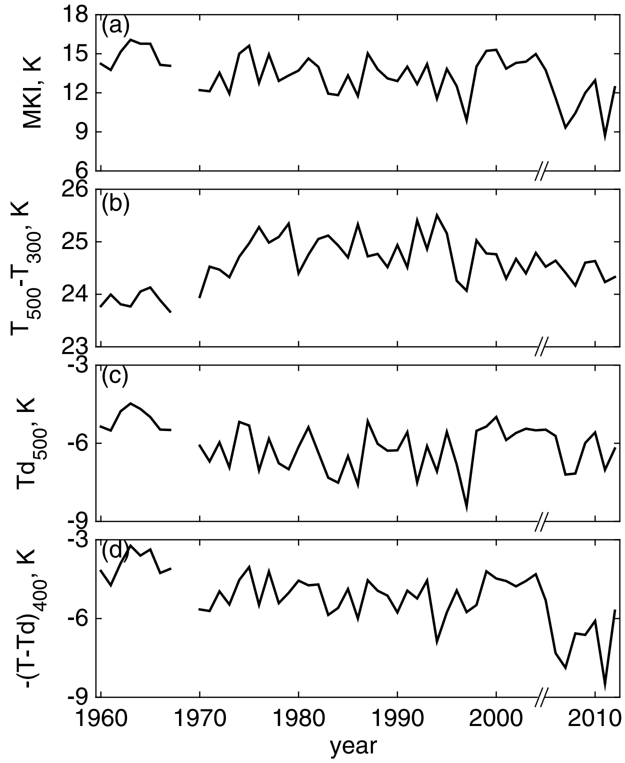

Figure 3. The variation of modified *K* index (MKI) and related terms. (a) MKI, (b) $T_{500} - T_{300}$, (c) T_{d500}, and (d) $-(T - T_d)_{400}$ in Nagqu from 1960 to 2012 (unit: K).

3.2. Physical Explanations for Changes of SDs

3.2.1. Preconditions for Severe Storm in the TP

We examine both the dynamic and thermodynamic factors influencing the occurrence of severe storm and show the results in Figure 2 by comparing the parameters on storm day, no-storm day (NSD), and hail day (HD).

Figure 2 shows that all variables differ between the SD and the NSD over TP. To be specific, the distribution of PW/CAPE on SDs presents the same range as on NSDs, while the dispersion of MKI on SD is much smaller than that on NSDs, indicating that MKI is more capable of distinguishing the day with or without severe storm than PW/CAPE. Moreover, the correlation coefficients between PW and SD, and CAPE and SD, are 0.26 and 0.31, respectively, and not significant. While the correlation between MKI and SD is 0.59, significant at 0.01 level. Besides, the trends of PW and CAPE are both positive, suggesting that they provide more favorable conditions for storm formation. These are opposite to the observation that storm days decrease with time. Representing the instability of atmosphere, MKIs with higher values indicate higher possibilities that thunderstorm occurs (George, 1960). Over TP MKI decreases significantly at a rate of −0.48 K/decade, agreeing with reduction of SD with time. As for VWS, the variation is also positively related to SD with the correlation coefficient 0.42 (significant at 0.05 level), weaker than the relation between MKI and SD.

Accordingly, for the TP, MKI plays the most important role in illustrating the environmental differences between SD and NSD. In the following subsection, we will discuss the physical mechanism how changes in atmospheric instability (MKI) impact the changes of SD.

3.2.2. Roles of Drier Midtroposphere in the Variation of SD

A decreasing trend of MKI (significant at 0.05 level) is observed during the period from 1960 to 2012 (Figure 3a), which suggests that the atmosphere has become more stable over TP. We calculated the correlation coefficient between the MKI and SD. During 1960–2012, 1960–2004, and 2005–2012, they are 0.59 (significant at the 0.01 level), 0.49 (significant at the 0.01 level), and 0.27 (period too short to do significant test), respectively. A comparison of the correlation coefficients between each term of the MKI (see equation (1)) and the MKI indicated that midtropospheric humidity, as represented by the depression of dew point at 400 hPa (Figure 3d), is the dominant term for the change of MKI. The decreasing midtropospheric humidity (Figure 3d) tends to suppress convective activity (Gerken et al., 2015; Roca et al., 2005). The results indicate that compared with the other two terms of MKI, the midtropospheric moisture plays a more important role in generating atmospheric instability over TP. The drying tendency due to a rapid increase of temperature in a warming climate (Duan & Xiao, 2015) has led to a decrease in the SD during the last five decades.

3.3. Physical Explanations for Changes of HDs

A decreasing of MKI has contributed to the decline of SD over TP. However, variations/trends on HDs differ from those on SDs during the same period (Figure 2). What cause such discrepancies? Figures 2d and 2h demonstrate that hail occurrence requires stronger wind shear, which is believed to be favorable for convection initiation (Lee et al., 1991). Previous studies confirm that MLH plays a crucial role in hail occurrence by influencing the melting layer thickness (Xie et al., 2008). Thus, MLH and VWS are discussed here (Figure 4a). It is found that the mean MLH increases during 1973–2012 and VWS decreases during 1980–2012 significantly (Figure 4a). The correlation coefficient between the mean MLH (VWS) and HD during 1973–2012 (1980–2012) is −0.35 (0.5), both significant at the 0.05 level. These results further confirm that MLH and VWS are two crucial parameters for determining hail occurrence during SDs over TP.

Owing to the scarcity of continuous sounding before 1973 (1980) to determine MLH (VWS) at Nagqu, we could only answer this question by comparing differences between the years with more and less HD (i.e., THY and BHY; see section 2). Composite analysis shows that MLH is about 50 gpm lower (Figure 4b) and

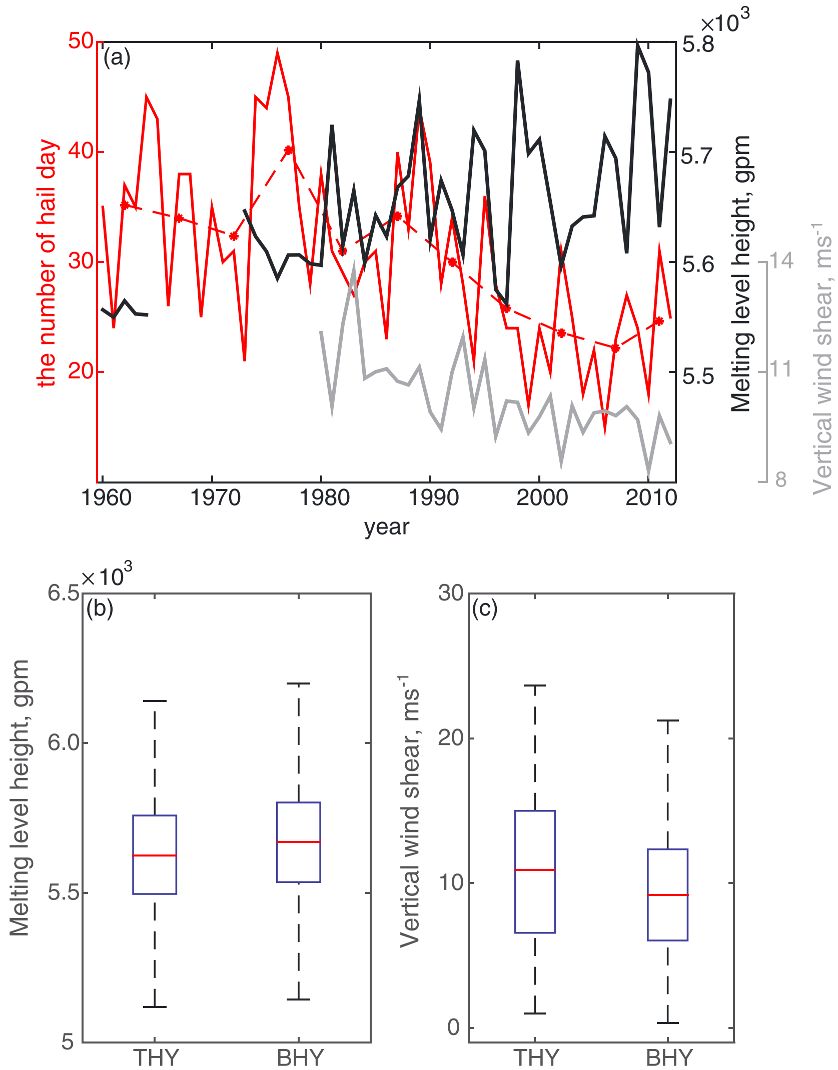

Figure 4. Mean and distributions of melting level height (MLH) and vertical wind shear (VWS) in Nagqu. (a) The time series of warm season mean MLH (black line), VWS (gray line), and hail day (HD; red line) during 1960 to 2012. The box and whisker plots of (b) MLH (unit: gpm) and (c) VWS (unit: m/s) on storm days in the years with which HD is in top hail year and bottom hail year.

VWS is 2 m/s higher (Figure 4c) in the THYs compared to the BHYs. The differences in the distributions of MLH and VMS are all significant at the 0.01 level based on a Student *t* test.

A decline in the number of HD is largely determined by changes in both thermodynamic (MLH) and dynamical (VWS) parameters. The slightly decreasing trends of MLH during 1973–1980 suggest that the large-scale thermodynamic conditions likely play an important role in hail occurrence during this period. After 1980, the MLH displays a positive trend (14 gpm/decade, significant at the 0.05 level), and VMS weakens ($-1.2\ ms^{-1}$/decade, significant at the 0.01 level), indicating that the thermodynamic and dynamic factors work together to produce a decrease of HD at Nagqu.

3.4. Changes of Favorable Parameters Over TP Area Derived From Reanalysis Data

To obtain a deeper understanding of the changes in the frequency of HD and SD in the TP, we analyzed the MKI, MLH, and VWS using NCEP/NCAR reanalysis data, focusing on the grids where observation stations are located at. Figure 5a shows a significant decline in SD at most stations, consistent with the negative trend of MKI values during 1960–2012. The negative trends of SD and MKI values are more obvious after 1980

10.1029/2018GL077069

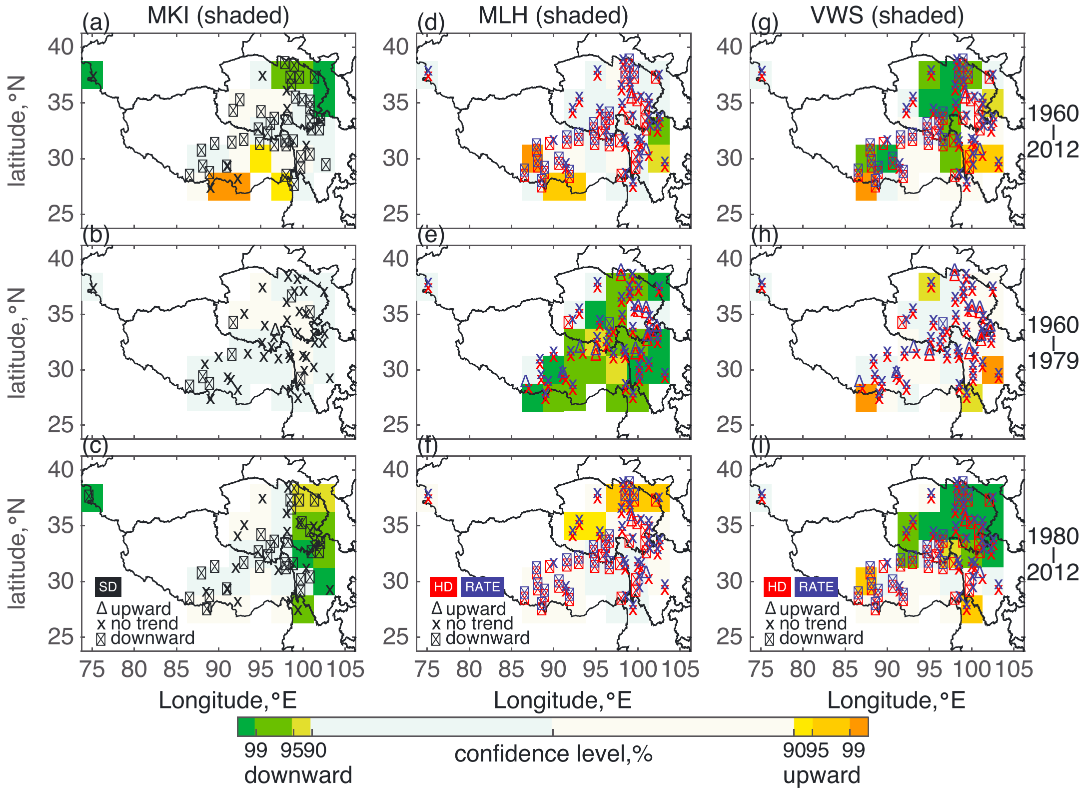

Figure 5. Trends of (left) modified *K* index (MKI), (middle) melting level height (MLH), and (right) vertical wind shear (VWS) at 06 local solar time during (top) 1960–2012, (middle) 1960–1979, and (bottom) 1980–2012 calculated using National Centers for Environmental Prediction/National Center for Atmospheric Research reanalysis data. (a–c) Trends of MKI (shaded) and storm day (SD, black symbols); (d–f) trends of MLH (shaded) on storm days, hail day (HD; red symbols), and the ratio of HD to SD (blue symbols); and (g–i) same as Figures 5d–5f, except for VWS. The downward (upward) trends of MKI, MLH, and VWS are plotted in cold (warm) colors, respectively; the color-bar labels indicate their confidence level. Δ, ∇, and × represent upward, downward, no significant trends of SD, HD, and ratio of HD to SD, separately. Only grids with observation stations are shown.

(Figure 5c) compared with those during 1960–1979. The decline in MKI values is mainly associated with a drying midtroposphere, that is, a downward trend of $T - T_d$ at 400 hPa. The correlation coefficient between the domain-averaged MKI and the $(T - T_d)_{400}$ is 0.84 (significant at the 0.01 level) during 1960–2012. The reanalysis results infer that the number of SD has decreased in the TP, mainly because of a drier and more stable atmosphere as climate warms.

Changes in HD display different trends during the two periods 1960–1979 (Figure 5e) and 1980–2012 (Figure 5f). Unlike the negative HD trend after 1980 over most areas of the TP (Figure 5f), there is no significant HD trend before 1980 over TP except five stations. Analysis of the key thermodynamic (MLH) and dynamic (VWS) parameters suggests that decreases in MLH during 1960–1979 contribute to the different trends in the number of HD during the two periods. Specifically, the trend of MLH is significantly negative (shaded in cold colors in Figure 5e) over most of the TP, while the few stations with a positive trend are not significant. Wind shear becomes weaker east of 90°E (Figure 5h). The effects of the thermodynamic (MLH) and dynamic (VWS) parameters are in opposition, leading to a nonsignificant change in the number of HD before 1980. After 1980, the MLH trend becomes positive, inhibiting hail formation (Figure 5f). Thus, the numbers of both SD and HD began to decrease.

4. Conclusions

The TP has warmed twice as fast as most places on Earth during the past 50 years (Liu & Chen, 2000; Duan & Xiao, 2015). Such an unprecedented warming rate has changed the large-scale thermodynamic and dynamical conditions in the region and impacted on climate extremes such as the frequencies of SD and

HD. The results of this study suggest that a drying midtroposphere due to the strong surface warming is the primary reason for the decrease of warm-season SD in the TP since 1960. The warmer atmosphere has increased the height of the melting level, mainly after 1980, and led to a decline in the number of HD combined with a weaker wind shear. These results imply that global warming is likely to cause a decrease in the conditions required for severe thunderstorm and hail formation in the TP over the next century.

Acknowledgments
This study is supported by the Chinese National Science Foundation under grant 41330421. The first author gratefully acknowledges the financial support from the China Scholarship Council. The weather phenomenon record data, station sounding data, and surface observation data are obtained from CMA/NMIC; the reanalysis data are provided by NCEP/NCAR.

References

American Meteorological Society (2017). “Severe storm”. Glossary of Meteorology http://glossary.ametsoc.org/wiki/Severe_storms

Berthet, C., Dessens, J., & Sanchez, J. L. (2011). Regional and yearly variations of hail frequency and intensity in France. *Atmospheric Research*, *100*(4), 391–400. https://doi.org/10.1016/j.atmosres.2010.10.008

Cao, Z. (2008). Severe hail frequency over Ontario, Canada: Recent trend and variability. *Geophysical Research Letters*, *35*, L14803. https://doi.org/10.1029/2008GL034888

Changnon, S. A., & Changnon, D. (2000). Long-term fluctuations in hail incidences in the United States. *Journal of Climate*, *13*(3), 658–664. https://doi.org/10.1175/1520-0442(2000)013%3C0658:LTFIHI%3E2.0.CO;2

Dessens, J., Berthet, C., & Sanchez, J. L. (2015). Change in hailstone size distributions with an increase in the melting level height. *Atmospheric Research*, *158-159*, 245–253. https://doi.org/10.1016/j.atmosres.2014.07.004

Doswell, C. A. III, Brooks, H. E., & Kay, M. P. (2005). Climatological estimates of daily local nontornadic severe thunderstorm probability for the United States. *Weather Forecasting*, *20*(4), 577–595. https://doi.org/10.1175/WAF866.1

Duan, A., & Xiao, Z. (2015). Does the climate warming hiatus exist over the Tibetan Plateau? *Scientific Reports*, *5*(1), 13711. https://doi.org/10.1038/srep13711

George, J. J. (1960). *Weather forecasting for aeronautics*. New York and London: Academic Press.

Gerken, T., Biermann, T., Babel, W., Herzog, M., Ma, Y., Foken, T., & Graf, H. (2015). A modelling investigation into lake-breeze development and convection triggering in the Nam Co Lake basin, Tibetan Plateau. *Theoretical and Applied Climatology*, *117*(1-2), 149–167. https://doi.org/10.1007/s00704-013-0987-9

Hamed, K. H., & Rao, A. R. (1998). A modified Mann-Kendall trend test for autocorrelated data. *Journal of Hydrology*, *204*(1-4), 182–196. https://doi.org/10.1016/S0022-1694(97)00125-X

John, R. H., & Doswell, C. A. III (1992). Severe local storms forecasting. *Weather Forecasting*, *7*(4), 588–612. https://doi.org/10.1175/1520-0434(1992)007%3C0588:SLSF%3E2.0.CO;2

Kendall, M. G. (1955). Rank correlation methods. *Biometrika*, *34*, 108.

Kunz, M., Sander, J., & Kottmeier, C. (2009). Recent trends of thunderstorm and hailstorm frequency and their relation to atmospheric characteristics in southwest Germany. *International Journal of Climatology*, *29*(15), 2283–2297. https://doi.org/10.1002/joc.1865

Lee, B. D., Farley, R. D., & Hjelmfelt, M. R. (1991). A numerical case study of convection initiation along colliding convergence boundaries in northeast Colorado. *Journal of the Atmospheric Sciences*, *48*(21), 2350–2366. https://doi.org/10.1175/1520-0469(1991)048%3C2350:ANCSOC%3E2.0.CO;2

Li, M., Zhang, Q., & Zhang, F. (2016). Hail day frequency trends and associated atmospheric circulation patterns over China during 1960–2012. *Journal of Climate*, *29*(19), 7027–7044. https://doi.org/10.1175/JCLI-D-15-0500.1

Liu, X., & Chen, B. (2000). Climate warming in the Tibetan Plateau during recent decades. *International Journal of Climatology*, *20*(14), 1729–1742. https://doi.org/10.1002/1097-0088(20001130)20:14%3C1729::AID-JOC556%3E3.0.CO;2-Y

Mahoney, K., Alexander, M. A., Thompson, G., Barsugli, J. J., & Scott, J. D. (2012). Changes in hail and flood risk in high-resolution simulations over Colorado’s mountains. *Nature Climate Change*, *2*(2), 125–131. https://doi.org/10.1038/nclimate1344

Mann, H. B. (1945). Nonparametric tests against trend. *Econometrica*, *13*(3), 245. https://doi.org/10.2307/1907187

Markowski, P., & Richardson, Y. (2010). *Mesoscale meteorology in midlatitudes*. Chichester, UK: John Wiley. https://doi.org/10.1002/9780470682104

Mezher, R. N., Doyle, M., & Barros, V. (2012). Climatology of hail in Argentina. *Atmospheric Research*, *114-115*, 70–82. https://doi.org/10.1016/j.atmosres.2012.05.020

Niall, S., & Walsh, K. (2005). The impact of climate change on hailstorms in southeastern Australia. *International Journal of Climatology*, *25*(14), 1933–1952. https://doi.org/10.1002/joc.1233

Púčik, T., Groenemeijer, P., Rýva, D., & Kolář, M. (2015). Proximity soundings of severe and nonsevere thunderstorms in Central Europe. *Monthly Weather Review*, *143*(12), 4805–4821. https://doi.org/10.1175/MWR-D-15-0104.1

Roca, R., Lafore, J. P., Piriou, C., & Redelsperger, J. L. (2005). Extratropical dry-air intrusions into the West African monsoon midtroposphere: An important factor for the convective activity over the Sahel. *Journal of the Atmospheric Sciences*, *62*(2), 390–407. https://doi.org/10.1175/JAS-3366.1

Tang, N., Liu, Y., Li, G., & Li, F. (2014). New issue of relative humidity observations in the middle and low troposphere: Preliminary analysis on abnormally dry phenomena of the Chinese L-band radiosonde system (in Chinese). *Journal of Tropical Meteorology*, *30*, 643–653.

Tuovinen, J. P., Punkka, A. J., Rauhala, J., Hohti, H., & Schultz, D. M. (2009). Climatology of severe hail in Finland: 1930–2006. *Monthly Weather Review*, *137*(7), 2238–2249. https://doi.org/10.1175/2008MWR2707.1

Weisman, M. L., & Klemp, J. B. (1982). The dependence of numerically simulated convective storms on vertical wind shear and buoyancy. *Monthly Weather Review*, *110*(6), 504–520. https://doi.org/10.1175/1520-0493(1982)110%3C0504:TDONSC%3E2.0.CO;2

Williams, E., & Renno, N. (1993). An analysis of the conditional instability of the tropical atmosphere. *Monthly Weather Review*, *121*(1), 21–36. https://doi.org/10.1175/1520-0493(1993)121%3C0021:AAOTCI%3E2.0.CO;2

Xie, B., Zhang, Q., & Wang, Y. (2008). Trends in hail in China during 1960–2005. *Geophysical Research Letters*, *35*, L13801. https://doi.org/10.1029/2008GL034067

Xu, W., & Zipser, E. J. (2011). Diurnal variations of precipitation, deep convection, and lightning over and east of the eastern Tibetan Plateau. *Journal of Climate*, *24*(2), 448–465. https://doi.org/10.1175/2010JCLI3719.1

You, W., Zang, Z., Pan, X., Li, Y., An, C., & Li, A. (2012). Statistical analyses on characteristic and environmental aspect of summer thunderstorms over the Tibetan Plateau (in Chinese). *Plateau Meteorology*, *31*(6), 1523–1529.

Zhang, C., Zhang, Q., & Wang, Y. (2008). Climatology of hail in China: 1961–2005. *Journal of Applied Meteorology and Climatology*, *47*(3), 795–804. https://doi.org/10.1175/2007JAMC1603.1

Zhang, Q., Ni, X., & Zhang, F. (2017). Decreasing trend in severe weather occurrence over China during the past 50 years. *Scientific Reports*, *7*, 42,310. https://doi.org/10.1038/srep42310