CLIMATE CHANGE

Rapid decadal convective precipitation increase over Eurasia during the last three decades of the 20th century

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Convective precipitation—localized, short-lived, intense, and sometimes violent—is at the root of challenges associated with observation, simulation, and prediction of precipitation. The understanding of long-term changes in convective precipitation characteristics and their role in precipitation extremes and intensity over extratropical regions are imperative to future water resource management; however, they have been studied very little. We show that annual convective precipitation total has been increasing astonishingly fast, at a rate of 18.4%/°C, of which 16% is attributable to an increase in convective precipitation occurrence, and 2.4% is attributable to increased daily intensity based on the 35 years of two (combined) historical data sets of 3-hourly synoptic observations and daily precipitation. We also reveal that annual daily precipitation extreme has been increasing at a rate of about 7.4%/°C in convective events only. Concurrently, the overall increase in mean daily precipitation intensity is mostly due to increased convective precipitation, possibly at the expanse of nonconvective precipitation. As a result, transitional seasons are becoming more summer-like as convective becomes the dominant precipitation type that has accompanied higher daily extremes and intensity since the late 1980s. The data also demonstrate that increasing convective precipitation and daily extremes appear to be directly linearly associated with higher atmospheric water vapor accompanying a warming climate over northern Eurasia.

INTRODUCTION

Precipitation over high latitudes has experienced complex changes in character and seasonality under a warming climate that could lead to serious consequences of disparity between water demand and supply. For example, shortened snowfall season and reduced snowfall events during the transitional seasons of spring and fall (*1*–*3*) may increase growing season length, driving a higher demand for water supply. At the same time, precipitation has become more extreme (*4*–*6*) and of higher intensity (*7*–*9*), which has led to increased frequency and severity of flooding events and drought episodes, as frequently reported in the news media [for example, Lehner *et al.* (*10*) and Schubert *et al.* (*11*)]. These changes demand new infrastructure to quickly capture or divert downpours to relieve flooding and conserve water for dry periods.

Precipitation can be divided into two categories based on different atmospheric processes: (i) nonconvective (or stratiform), which is the steady, sustained rain or snow associated with large-scale forced ascent and/or detrainment, and (ii) convective, which is the intermittent bursts of liquid or solid precipitation, sometimes of very high intensity, associated with local convective air circulation (*12*). Convective precipitation has much smaller spatial scales and shorter temporal scales, which makes it more challenging to simulate, predict, and observe.

Current climate model simulations tend to produce dry biases for precipitation events of convective nature. For example, they underestimate precipitation over wet regions and in warm seasons over East Asia and China (*13*, *14*), where convective precipitation is dominant. Simulation of tropical precipitation extremes is very inconsistent among different models with variations larger than signals by a factor of 2.5 (*15*). CMIP5 and regional models underestimate convective precipitation totals and extremes but overestimate those quantities in nonconvective precipitation (*16*, *17*). The inability of coarse-resolution climate models to accurately represent small-scale convective properties is partly to blame (*18*).

Sensitivity to increasing air temperature of these two types of precipitation at subdaily time scales has been explored by a few researchers. For example, Berg *et al.* (*19*, *20*) found that convective precipitation is more sensitive to increasing air temperature and becomes more dominant at higher temperatures over southwestern Germany and that the super Clausius-Clapeyron increase is due to the transition from dominant nonconvective to more dominant convective precipitation (*21*). In tropics, Wong and Teixeira (*22*) indicate that the development of extreme convective events is more sensitive to changes in sea surface temperature.

Exploring the long-term changing behavior of convective and nonconvective precipitation in relation to warming climate and rising atmospheric water vapor in observation is needed to validate current climate model simulations. This would potentially improve future projections of precipitation characteristics. Furthermore, uncovering the unique changing characteristics of both precipitation types and their different roles in overall precipitation trends, intensity, and extremes would advance the prediction of changing hydrological cycles and would greatly assist with water resource management. Northern Eurasia—the largest piece of habitable land in high latitudes and an area with an amplified seasonal response to warming climate—is an ideal place to search for these signals.

This study combines 3-hourly synoptic weather observations with daily precipitation records to separate daily precipitation events into three categories of convective, nonconvective, and mixed (both convective and nonconvective occurring within 24 hours) at 152 stations across northern Eurasia. Then, the annual and seasonal trends of precipitation total (accumulated amount), extreme (maximum daily precipitation), and daily intensity (mean daily precipitation for wet days only) for each category and their relationships with surface air temperatures and specific humidity during 1966–2000 are examined both locally and regionally.

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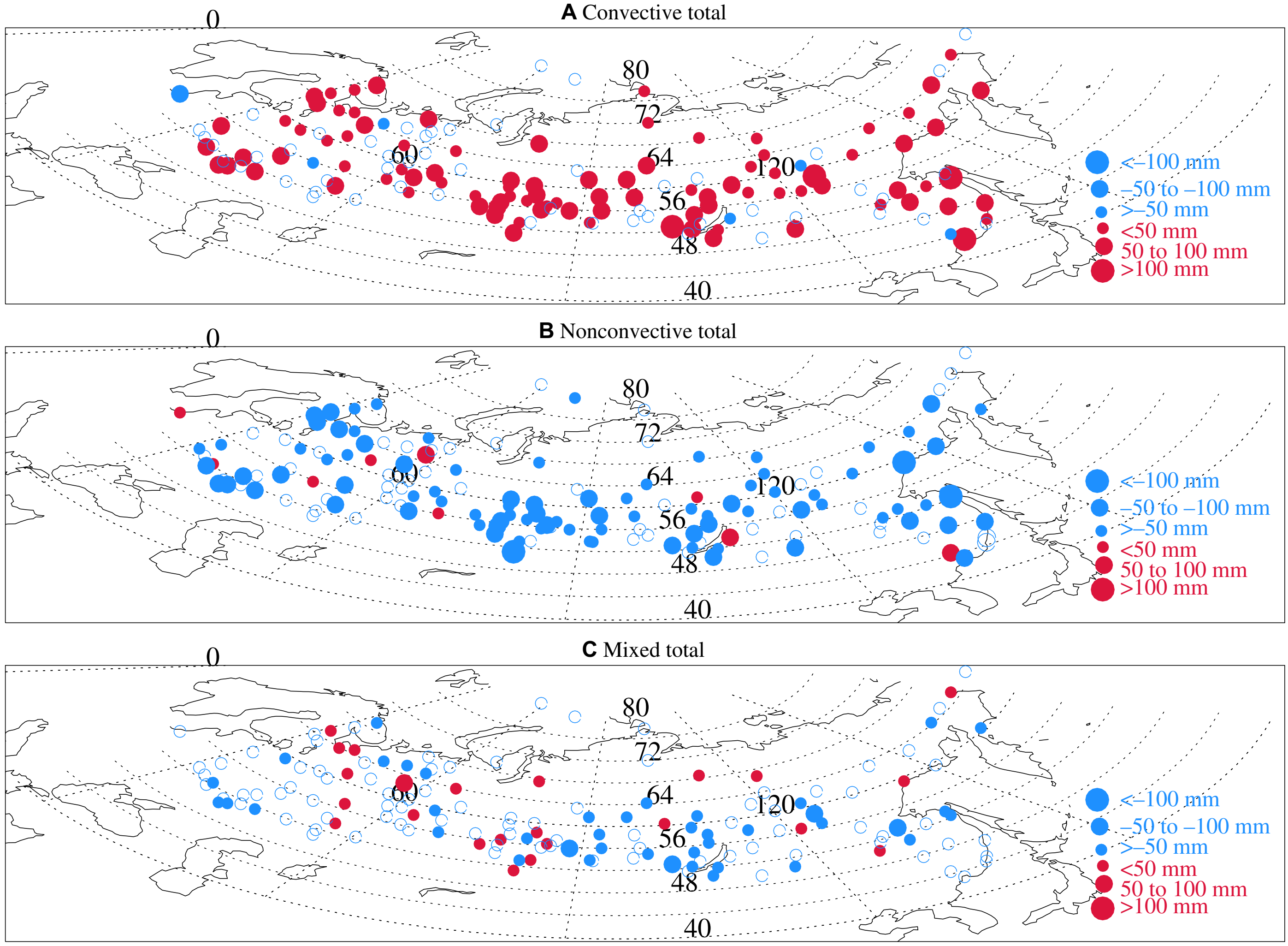
RESULTS

Decadal trends

The annual precipitation totals contributed by convective events have been increasing, whereas those contributed by nonconvective and mixed events have been decreasing across the study region during 1966–2000. Figure 1A shows that 94 (61.8%) stations have statistically significant positive trends compared to only 6 (3.9%) stations that have statistically significant negative trends for annual convective precipitation total. Meanwhile, 90 (59.2%) stations have statistically significant negative trends for nonconvective precipitation (Fig. 1B), and 41 (27.0%) stations have statistically significant negative trends for mixed precipitation (Fig. 1C). The rate of change ranged from −59.0 to 131.8 mm per decade for convective and −155.9 to 54.7 mm per decade for nonconvective precipitation among 152 stations.

The time series of mean annual precipitation total, frequency, and mean daily intensity averaged from all available stations shows that convective precipitation total, frequency, and intensity have been increasing rapidly at 36.7 mm, 8.5 days, and 0.14 mm/day per decade, respectively. At the same time, nonconvective precipitation total, frequency, and intensity have been decreasing at 32.6 mm, 11.8 days, and 0.08 mm/day per decade (Fig. 2). Convective precipitation total replaced nonconvective precipitation as the dominant precipitation contributor in 1983, whereas convective precipitation frequency caught up with that of nonconvective precipitation at the end of the study period in the late 1990s. Mixed precipitation total has also been declining slightly at 5.2 mm along with decreasing intensity of 0.21 mm/day per decade, with no significant change in its frequency. As a result, the annual mean daily precipitation intensity has also been increasing steadily when all categories are combined at about 0.1 mm/day per decade. All these trends are statistically significant at a 99% confidence level. This is consistent with earlier studies that revealed that mean daily precipitation intensity has been increasing under the background of warming and moistening atmosphere (*7*, *9*) over northern Eurasia.

The increasing convective intensity is most likely due to a faster increase in its precipitation total than its frequency, whereas the increasing nonconvective precipitation intensity is likely due to a faster decrease in its frequency compared to that of total. Examining the averaged time series of annual mean fractions of convective, nonconvective,


A Convective total

B Nonconvective total

C Mixed total

Fig. 1. Geographical distribution of annual precipitation total trends. (**A**) Convective, (**B**) nonconvective, and (**C**) mixed precipitation (red circles, positive trend; blue circles, negative trend; shaded circles, statistically significant at a 95% confidence level or higher). The size of the shaded circle represents the magnitude of trend of millimeter per decade.

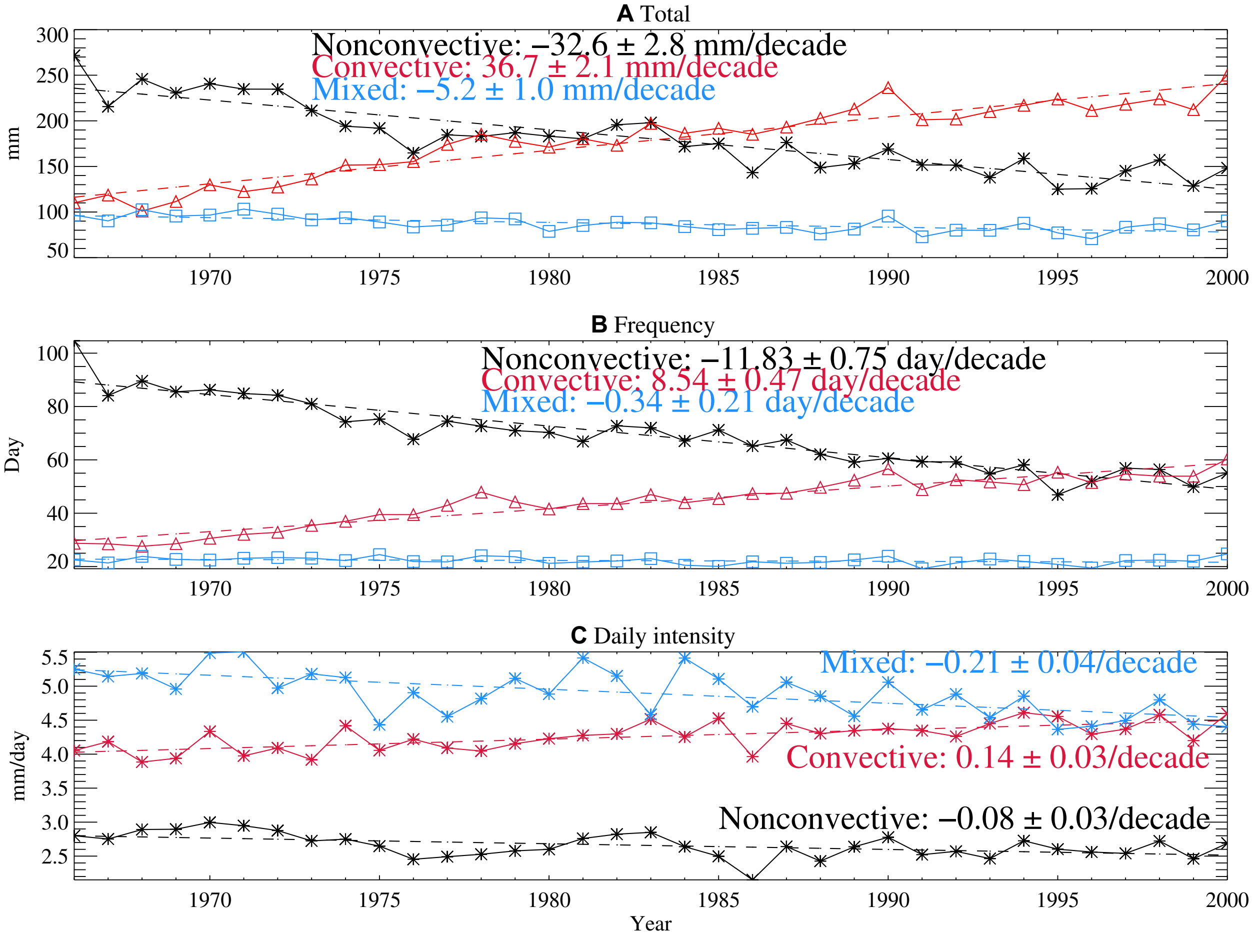


Fig. 2. Averaged time series from all stations for precipitation total, frequency, and daily intensity. Mean time series of (**A**) annual total (mm), (**B**) frequency (day), and (**C**) mean daily intensity (mm/day) averaged from all available stations for three categories and their linear trends (plus and minus indicate one σ value).

and mixed precipitation days (divided by all wet days) shows that convective precipitation increased from around 18 to 43%, whereas nonconvective precipitation decreased from around 68 to 39% during the study period of 1966–2000 (fig. S1). By the end of the study period, convective precipitation became the dominant precipitation type over the study region. There is no significant change in mixed precipitation fraction throughout the study region.

Similar significant trends are found in all seasons except winter, during which mixed precipitation has also been increasing (Fig. 3). It is clear that nonconvective precipitation dominates during winter, and convective precipitation dominates during summer. The shift of prevalence from nonconvective to convective precipitation during spring and fall seasons started in the late 1980s.

The annual trends for daily precipitation extreme (the annual maximum daily accumulation for each precipitation category) behave similarly to that of precipitation total. Dominant positive trends are found in the convective category, whereas negative trends are found in both nonconvective and mixed precipitation categories. The annual mean daily extreme for convective precipitation has been increasing at 1.8 mm per decade, whereas the nonconvective extreme has been decreasing at 2.5 mm per decade; the mixed extreme has been decreasing at 1.3 mm per decade averaged from all available stations (fig. S2). It is also clear that convective extremes have become higher than that of nonconvective extremes since 1974. However, if we do not separate precipitation into different categories, then there is no significant trend in annual daily extremes averaged over the study region (fig. S2).

From a seasonal perspective, daily precipitation extreme during winter has been associated with nonconvective precipitation, probably because of its dominance during winter, but has been decreasing. However, the daily extreme associated with convective and mixed precipitation has been increasing during winter (Fig. 4A). The highest daily extreme occurred during summer, and its trend obviously resembles that of the annual daily extreme (Fig. 4C). In the late 1980s, the highest daily extreme among these three precipitation categories started to occur in the convective rather than the nonconvective precipitation during the transitional seasons of spring and fall (Fig. 4, B and D). Daily precipitation extreme without discriminating among different precipitation categories has no significant trends for all seasons (Fig. 4, dashed green line).

Daily precipitation intensity has been increasing for all precipitation categories during both winter (the lowest mean daily intensity) and summer (the highest mean daily intensity; fig. S3). This is consistent with an earlier study of increasing daily precipitation intensity in both the top 70th and bottom 30th percentile (*7*) at an interannual time scale. For spring and fall, the significant increasing

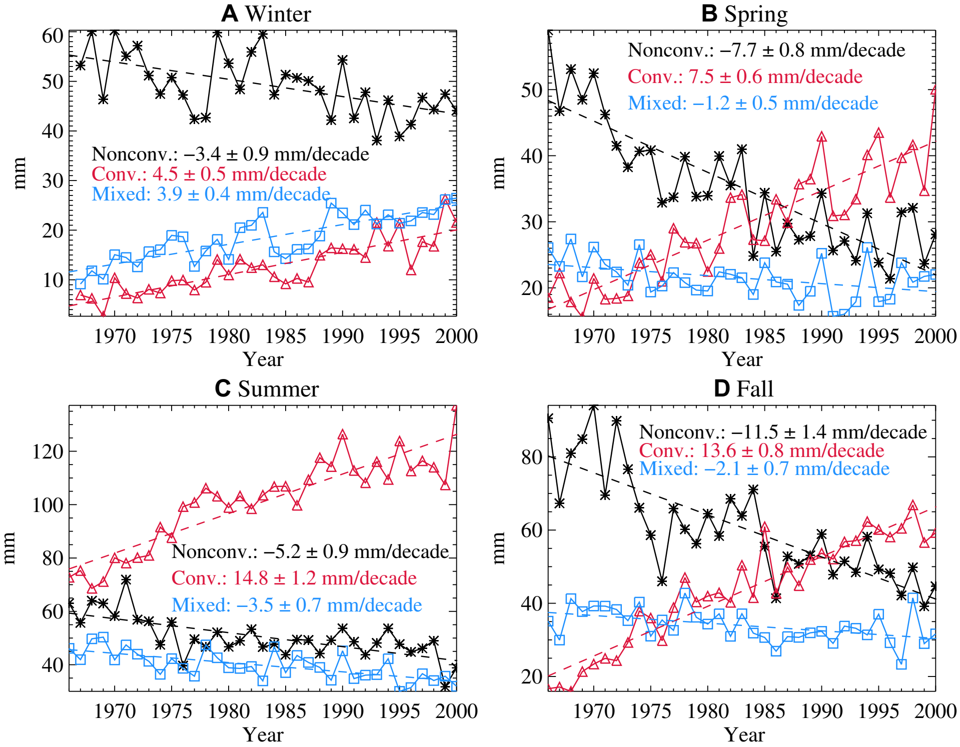


Fig. 3. Seasonal time series of precipitation total associated with the convective (red), nonconvective (black), and mixed precipitation (blue) days averaged from all available stations. (**A**) Winter, (**B**) spring, (**C**) summer, and (**D**) fall. Trend lines are all statistically significant at a 95% confidence level or higher. Plus and minus values are the σ sigma for the trend line.

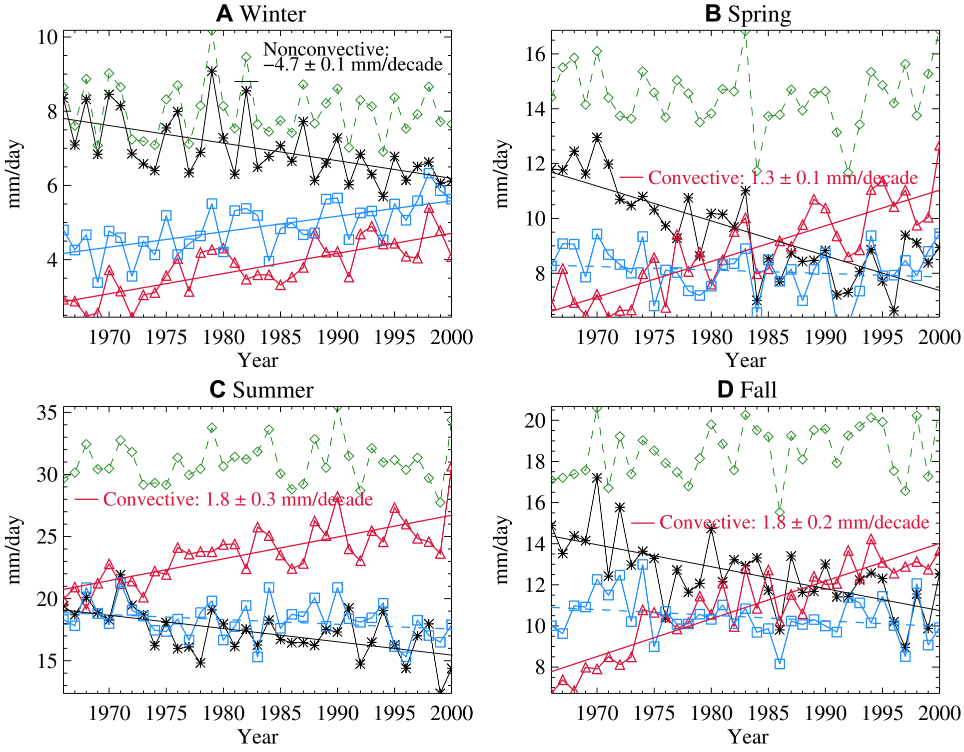


Fig. 4. Seasonal time series of daily precipitation extreme for convective (red), nonconvective (black), mixed (blue), and all events (green dashed line) averaged from all available stations. (**A**) Winter, (**B**) spring, (**C**) summer, and (**D**) fall. Solid straight lines are statistically significant, and dashed lines represent no statistically significant trends.

daily precipitation intensity only occurred in convective precipitation. Thus, convective precipitation is the major driver for the overall increase in precipitation daily intensity (*7*) during transitional seasons. Not surprisingly, daily mean convective precipitation intensity exceeded that of nonconvective in the late 1980s during spring and fall (fig. S3), coinciding with that of daily extremes in Fig. 4 (B and D). It is clear that convective precipitation is the driver for increases in daily intensity and extremes for all seasons.

Relationship with temperature and specific humidity

To have a perspective on how these precipitation characteristics change corresponding to the overall warming and moistening of the atmosphere, we examined the relationships of precipitation in each category with mean surface air temperature and specific humidity at both annual and seasonal time scales. The annual daily precipitation extreme for convective precipitation has increased at 7.4%/°C, with increasing surface annual mean air temperature averaged over the study region. At the same time, the daily extreme has decreased 8.5%/°C for nonconvective and 4.9%/°C for mixed precipitation, with increasing annual mean surface air temperature (Fig. 5A). However, annual convective precipitation total has increased by 18.4%/°C (Fig. 5B). At seasonal time scales, the spring convective daily extreme increased at 8.2%/°C, and summer convective daily extreme increased at 10.4%/°C of the corresponding seasonal air temperature increase, slightly higher than the annual daily extreme. The rate of annual mean daily precipitation intensity increased with air temperature at 2.4%/°C for convective precipitation but decreased at −3.8%/°C for mixed and −1.2%/°C for nonconvective precipitation. All these relationships are statistically significant at a 95% confidence level or higher. Thus, it appears that daily precipitation intensity contributes 2.4% to increases in convective totals, and the remaining 16% is contributed by increasing convective occurrence with each degree of air temperature increase.

The strongest linear relationship is between daily extreme of convective precipitation and specific humidity. The very close resemblance of interannual variation between convective daily extreme and specific humidity averaged from all available stations is evident in a very high correlation coefficient of 0.74 (Fig. 6). The small change in annual mean specific humidity of about 0.65 g/kg during the 35-year study period translates into about a 9.16-mm/day increase in daily extreme based on an average rate of 14.1 mm/day per g/kg increase in specific humidity. This positive linear relationship is also dominant at local stations for convective total and daily extreme (fig. S4). The statistically significant relationship is most reflected during summer and spring seasons. The increased rate for annual convective total is 18.6 mm/(g/kg), and the rate for mean daily intensity is 0.9 mm/day per g/kg, with all of them statistically significant at a 99.99% confidence level. There is no significant interannual relationship between precipitation total of nonconvective or mixed and specific humidity when trends are removed from time series.

DISCUSSION

Understanding the long-term changing behaviors of precipitation characteristics under a warming climate is challenging because precipitation is the mixed product of very different atmospheric processes of convective and nonconvective natures. This study separates precipitation

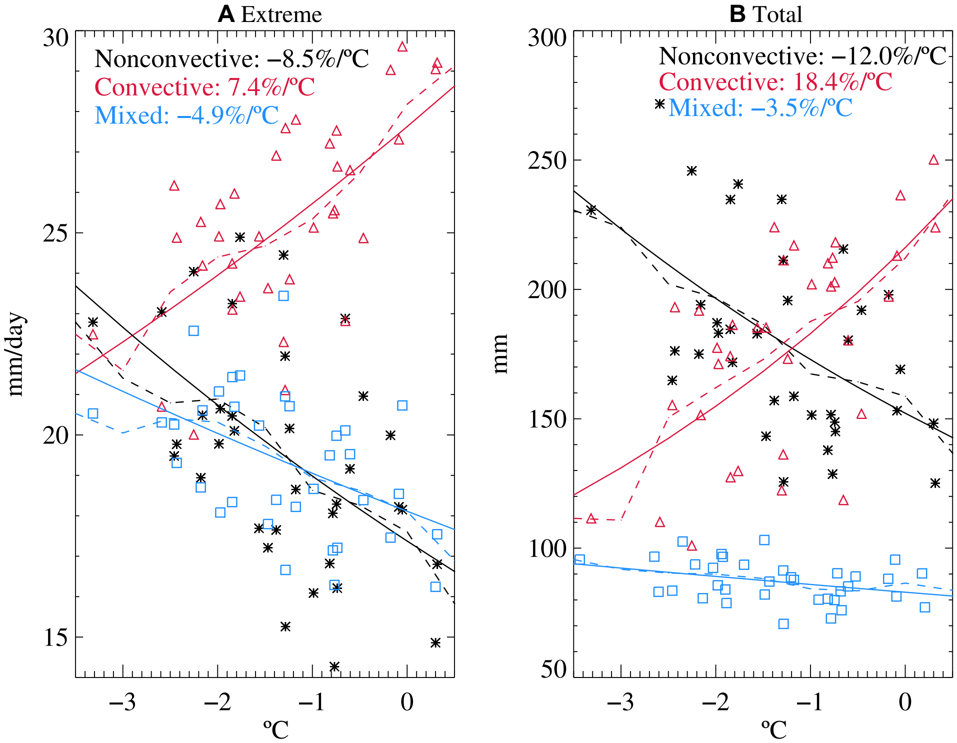


Fig. 5. Annual daily extremes and precipitation total plotted against the air temperature averaged from all available stations. (**A**) Annual daily precipitation extremes plotted against the annual mean surface air temperature averaged from all available stations for convective, nonconvective, and mixed precipitation. Dashed lines are the moving averages for each 1°C temperature increment. Solid lines are fitted for a constant rate of change (a) with air temperature change (ΔT) using $P = b(1 + a)^{\Delta T}$. (**B**) The same as (A) but for averaged annual precipitation total.

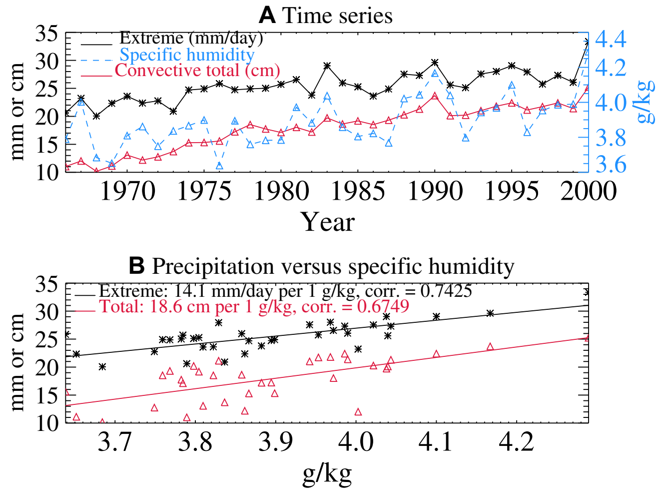


Fig. 6. Relationship of convective precipitation extreme and total to specific humidity. (**A**) Time series of daily convective precipitation extreme, total, and specific humidity averaged from all available stations for each year. (**B**) Scatterplot of convective extreme and total versus annual mean specific humidity with linear regression lines.

into three categories of convective, nonconvective, and mixed events to reveal their different sensitivities to a warming climate. We combine two historical observation data sets of 3-hourly synoptic observations and the daily precipitation records over northern Eurasia to identify 152 stations that contain both records to accomplish this partition. Strong and clear signals that are consistent among these stations and in all seasons suggest the following:

1. More frequent convective precipitation is responsible for increasing daily precipitation extreme and intensity.
2. Atmospheric water vapor appears to be directly linked to increased convective precipitation total and associated daily extremes and intensity under a warming climate.
3. The rapid increase in annual accumulated convective precipitation amounts may be occurring at the expense of nonconvective precipitation.

As a consequence, the transitional seasons of spring and fall are becoming more summerlike in terms of precipitation characteristics, extremes, and intensity.

The increasing convective precipitation may be explained by increasing convective available potential energy (CAPE) due to warming and moistening of the atmospheric boundary layer (*23*, *24*). A study over the eastern United States suggested that CAPE has a comparable magnitude of contribution as surface water vapor leading to higher precipitation intensity (*25*). The increasing extremes and intensity in convective precipitation may be linked to the invigoration of clouds via feedback with more water vapor that intensifies the convective process (*26*).

Changes in large-scale synoptic systems, such as decreasing Siberia high intensity, would decrease static stability and reduce lower-level cloud cover, which is mostly made up of stratiform clouds (*27*, *28*). The reduced occurrence of stratiform clouds would decrease nonconvective precipitation occurrence. More research, including modeling experiments, would help us shed light on the causes of our findings.

MATERIALS AND METHODS

We used daily precipitation records from the Daily Temperature and Precipitation Data for 518 Russian Meteorological Stations archived at the Carbon Dioxide Information Analysis Center (*9*, *29*). The precipitation characteristics, surface air temperatures, and humidity data came from the Global Synoptic Climatology Network, C: the former USSR, available from the National Climatic Data Center (2005) (*8*, *30*). This data set included 747 stations with 3-hourly observations of weather conditions. Here, convective precipitation included events of "showery precipitation" and "precipitation accompanied by current or recent thunderstorms" (code 80-99), and nonconvective precipitation included events of "precipitation that is both liquid and solid (code 60-69)" and "solid precipitation not in showers (code 70-79)." These observations were manually conducted by human observers who took visual inspections on precipitation types at regular observation times when other variables were collected (*30*). In addition to convective and nonconvective precipitation day categories, a third category of mixed precipitation day was used if both convective and nonconvective precipitation events were recorded during that day. Specific humidity was calculated from surface water vapor pressure and station pressure at each observation time (*8*, *31*).

Time series of precipitation total, daily extreme, and mean daily intensity were constructed for each category at each station for each season and year. The precipitation total was the accumulated daily precipitation amount (millimeters) during the corresponding season or year. The daily precipitation extreme was defined by the maximum daily precipitation during the corresponding season or year. The daily precipitation intensity was derived from the monthly precipitation total (summed from all daily precipitations) divided by the total number of days in which precipitation occurred; that is, it is the mean daily precipitation for all wet days. If more than 10% of records were missing, then that month/season/annual value was considered as missing for the station.

The starting year of 1966 was chosen because of a consistency in 3-hourly observation practice based on the standard Moscow time (but converted to local standard time in the data records) for synoptic observations (*30*) and consistent rain gauge types and quality control methods for precipitation records starting that year (*32*). The daily precipitation records consisted of the total accumulation for each calendar day. Although daily precipitation records ended in 2010, synoptic observations concluded at the end of 2000. Thus, the study time period was from 1966 to 2000. Matching between the daily precipitation data that had more than 25 years (of 518 precipitation stations) and weather condition observation data of more than 25 years (of 747 weather stations) colocated on the basis of a tolerance of 0.01°, which yielded 152 stations that were used for analyses [refer to Ye *et al.* (*9*) for details on data compilation]. For some seasons and some variables, a few stations might have less than 25 years of matching records between these two data sets; these stations were not included in the analyses for these particular seasons or variables to ensure a sample size of at least 25 years.

Spearman's rank correlation analysis, which is not sensitive to the statistical distribution of the data sets, was used to examine the trends and relationships with air temperature and specific humidity (*33*). This correlation method is very appropriate for small sample sizes, such as convective precipitation during winter and nonconvective precipitation during summer at some stations. Simple linear regression was used for trend analysis and relationships of precipitation with specific humidity. For relationships with surface air temperature, an exponential regression was used by fitting a least squares linear regression to the logarithm of precipitation $P = b(1 + a)^{\Delta T}$, in which ΔT is the air temperature change, and a is the constant rate of increase in precipitation (*34*). Here, statistical significance for any relationship was defined by a 95% confidence level or higher.

The averaged time series for the entire study region was constructed simply by averaging all available stations (unweighted) for the corresponding season or year to reflect a bigger picture of changes in the study region.

Because the results suggested that increases in convective frequency had contributed most (16%/°C) of the 18.4%/°C of convective precipitation total, changes in observation practices that discriminated between convective and nonconvective precipitation types are an important issue. The data document did not indicate changes in the methodology of precipitation-type observations (*30*) and did not reveal any discontinuity in the data (as determined by examining the time series of individual stations). In addition, the opposite trend between convective and nonconvective precipitation occurrence was generally consistent with increasing convective but decreasing stratiform cloud cover during all seasons over the study region (*27*, *28*). Given the large number of stations and human observers involved, the potential for systematic errors of individual human observers affecting precipitation and/or cloud types that might have affected our conclusions is very small.

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/3/1/e1600944/DC1

fig. S1. Annual time series of precipitation frequency for each precipitation category.
fig. S2. Annual time series of daily precipitation extreme for each precipitation category and all events.
fig. S3. Seasonal time series of daily precipitation intensity for each precipitation category.
fig. S4. Geographical distribution of relationships of convective precipitation total and extreme to specific humidity.

REFERENCES AND NOTES

1. H. Ye, M. Ellison, Changes in transitional snowfall season length in northern Eurasia. *Geophys. Res. Lett.* **30**, 561–563 (2003).
2. H. Ye, J. Cohen, Shortening snowfall season associated with increasing air temperature over northern Eurasia. *Environ. Res. Lett.* **8**, 014052 (2013).
3. H. Ye, Changes in frequency of precipitation types associated with surface air temperature over northern Eurasia during 1936–1990. *J. Climate* **21**, 5807–5819 (2008).
4. P. Y. Groisman, R. W. Knight, D. R. Easterling, T. R. Karl, G. C. Hegerl, V. N. Razuvaev, Trends in intense precipitation in the climate record. *J. Climate* **18**, 1326–1350 (2005).
5. C.-J. Shiu, S. C. Liu, C. Fu, A. Dai, Y. Sun, How much do precipitation extremes change in a warming climate? *Geophys. Res. Lett.* **39**, L17707 (2012).
6. S. Westra, L. V. Alexander, F. W. Zwiers, Global increasing trends in annual maximum daily precipitation. *J. Climate* **26**, 3904–3918 (2013).
7. H. Ye, E. J. Fetzer, S. Wong, A. Behrangi, D. Yang, B. H. Lambrigtson, Increasing atmospheric water vapor and higher daily precipitation intensity over northern Eurasia. *Geophys. Res. Lett.* **42**, 9404–9410 (2015).
8. H. Ye, E. J. Fetzer, S. Wong, A. Behrangi, E. T. Olsen, J. Cohen, B. H. Lambrigtsen, L. Chen, Impact of increased water vapor on precipitation efficiency over northern Eurasia. *Geophys. Res. Lett.* **41**, 2941–2947 (2014).
9. H. Ye, E. J. Fetzer, A. Behrangi, S. Wong, B. H. Lambrigtsen, C. Y. Wang, J. Cohen, B. L. Gamelin, Increasing daily precipitation intensity associated with warmer air temperatures over Northern Eurasia. *J. Clim.* **29**, 623–636 (2016).
10. B. Lehner, P. Döll, J. Alcamo, T. Henrichs, F. Kaspar, Estimating the impact of global change on flood and drought risks in Europe: A continental, integrated analysis. *Clim. Change* **75**, 273–299 (2006).
11. S. D. Schubert, H. Wang, R. D. Koster, M. J. Suarez, P. Y. Groisman, Northern Eurasian heat waves and droughts. *J. Clim.* **27**, 369–3107 (2014).
12. R Houze, Stratiform precipitation in regions of convection: A meteorological paradox? *Bull. Am. Meteorol. Soc.* **78**, 2179–2197 (1997).
13. S. Kusunoki, O. Arakawa, Are CMIP5 models better than CMIP3 models in simulating precipitation over East Asia? *J. Clim.* **28**, 5601–5621 (2015).
14. Q. Sun, C. Miao, Q. Duan, Comparative analysis of CMIP3 and CMIP5 global climate models for simulating the daily mean, maximum, and minimum temperatures and daily precipitation over China. *J. Geophys. Res.* **120**, 4806–4824 (2015).
15. P. A. O'Gorman, Sensitivity of tropical precipitation extremes to climate change. *Nat. Geosci.* **5**, 697–700 (2012).
16. J. Kyeslý, Z. Rulfová, A. Farda, M. Hanel, Convective and stratiform precipitation characteristics in an ensemble of regional climate model simulations. *Clim. Dyn.* **46**, 227–243 (2016).
17. N. Hirot, Y. N. Takayabu, A. Hamada, Reproducibility of summer precipitation over northern Eurasia in CMIP5 multi-climate models. *J. Clim.* **29**, 3317–3337 (2016).
18. E. J. Kendon, N. M. Roberts, H. J. Fowler, M. J. Roberts, S. C. Chan, C. A. Senior, Heavier summer downpours with climate change revealed by weather forecast resolution model. *Nat. Clim. Change* **4**, 570–576 (2014).
19. P. Berg, C. Moseley, J. O. Haerter, Strong increases in convective precipitation in response to higher temperatures. *Nat. Geosci.* **6**, 181–185 (2013).
20. P. Berg, J. O. Haerter, P. Thejll, C. Piani, S. Hagemann, J. H. Christensen, Seasonal characteristics of the relationship between daily precipitation intensity and surface temperature. *J. Geophys. Res.* **114**, D18102 (2009).
21. P. Berg, J. O. Haerter, Unexpected increase in precipitation intensity with temperature—A result of mixing precipitation types? *Atmos. Res.* **119**, 56–61 (2013).
22. S. Wong, J. Teixeira, Extreme convection and tropical climate variability: Scaling of cold brightness temperatures to sea surface temperature. *J. Clim.* **29**, 3893–3905 (2016).
23. C. Chou, C.-A. Chen, P.-H. Tan, K. T. Chen, Mechanisms for global warming impacts on precipitation frequency and intensity. *J. Clim.* **25**, 3291–3306 (2012).
24. B. Ye, A. D. Del Genio, K. K.-W. Lo, CAPE variations in the current climate and in a climate change. *J. Clim.* **11**, 1997–2015 (1998).
25. C. Lepore, D. Veneziano, A. Molini, Temperature and CAPE dependence on rainfall extremes in the eastern United States. *Geophys. Res. Lett.* **42**, 74–83 (2015).
26. S. Westra, H. J. Fowler, J. P. Evans, L. V. Alexander, P. Berg, F. Johnson, E. J. Kendon, G. Lenderink, N. M. Roberts, Future changes to the intensity and frequency of short-duration extreme rainfall. *Rev. Geophys.* **52**, 522–555 (2014).
27. B. Sun, P. Y. Groisman, Cloudiness variations over the former Soviet Union. *Int. J. Climatol.* **20**, 1097–1111 (2000).
28. B. Sun, P. Y. Groisman, I. I. Mokhov, Recent changes in cloud-type frequency and inferred increases in convection over the United States and the former USSR. *J. Clim.* **14**, 1864–1880 (2001).
29. O. N. Bulygina, V. N. Razuvaev, "Daily temperature and precipitation data for 518 Russian meteorological stations" (Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, 2012).
30. National Climatic Data Center, "Data Set 9290c: Global Synoptic Climatology Network. C. The former USSR" (National Climatic Data Center, 2005); www1.ncdc.noaa.gov/pub/data/documentlibrary/tddoc/td9290c.pdf.
31. J. P. Peixoto, A. H. Oort, *Physics of Climate* (American Institute of Physics, 1992).
32. P. Y. Groisman, E. G. Bogdanova, V. A. Alexeev, J. E. Cherry, O. N. Bulygina, Impact of snowfall measurement deficiencies on quantification of precipitation and its trends over northern Eurasia. *Ice Snow* **54**, 29–43 (2014).
33. D. S. Wilks, *Statistical Methods in the Atmospheric Sciences* (Academic Press, 1995), 467 pp.
34. G. Lenderink, E. van Meijgaard, Increase in hourly precipitation extremes beyond expectations from temperature changes. *Nat. Geosci.* **1**, 511–514 (2008).

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Science Advances

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