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THEMATIC ISSUE

Changes in event number and duration of rain types over Mongolia from 1981 to 2014

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Abstract In addition to the total amount of precipitation, the number, type and duration of rain events play a critical role in hydrological cycle, land surface processes, vegetation and land cover dynamics in such semi-arid regions as Mongolia where water availability is the main determinant of ecosystem functioning and services. However, only a limited number of studies have so far focused on certain aspects of changes in rain types and durations for Mongolia as a whole, while a relatively large number of studies have examined trends observed in total annual precipitation for the country. In the present study, we evaluated changes in not only the amount, but also in the number and total duration of rain types using the data on start-to-end times of all rain events from 55 meteorological stations scattered throughout Mongolia between 1981 and 2014, a period for which this type of analysis was made possible for the first time. Our study confirms that there has been no significant change in the amount of mean summer precipitation for almost all parts of the country for the last 34 years, with only a few stations showing a significant decreasing trend. In terms of rain types, the number and duration of convective rains have increased, while those of stratiform rain events have decreased over Mongolia, a trend that is more pronounced around Khangai mountain area in central Mongolia and south-eastern desert steppe and eastern steppe, suggesting a possible transition from stratiform rains to convective rains. The findings of this research imply that increasing temperature and altered rain type ratios may affect each other as the decreasing number and duration of stratiform rain events allow for progressively longer sunshine period, possibly feeding back to the increased temperature. The release of this latent heat fuelling the upward movement of moisture and producing the convective rains could be one of the reasons of the significant rise in convective rain frequency for the study period. The observed changes in rain patterns have significant implications in ecosystem functioning and resource management.

Keywords Precipitation patterns · Mongolia · Convective rain · Stratiform rain · Number and duration of rain events

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Introduction

Studies of yearly and seasonal precipitation on global and local scales reveal various trends over many regions of the world (Dore 2005; Endo et al. 2005; Krishnakumar et al.

2009; Méndez-Lázaro et al. 2014; Sayemuzzaman and Jha 2014). Changes in precipitation directly affect hydrology and functioning of ecosystems, as well as water resource management and agricultural production. For this reason, it is important to explore the changes in the spatial and temporal rainfall patterns to improve water management strategies (Cheng et al. 2006; McBean and Motiee 2008; Fu et al. 2013). Trenberth et al. (2003) emphasized that the characteristics of precipitation are as important as the amount. Researchers have reported massive decreases in light rains, decreases in the number of long duration rain events ($\geq$3 days) and decreases in the number of rainy days, while some increase in rain intensity or convective precipitation was observed mostly with the global warming in many regions of the world (Gong et al. 2004; Zhai et al. 2005; Liu et al. 2011; Berg et al. 2013; Westra et al. 2014).

Mongolia, one of the largest countries in territory, is experiencing some of the greatest rates of climate change, especially of annual temperature increase (Batima et al. 2005; Chen et al. 2009; Dagvadorj et al. 2014; Törnqvist et al. 2014). However, more careful analyses of the trends in precipitation are important because Mongolia is already semi-arid and contains the headwaters of some of the largest watersheds (e.g. Selenge and Amur) in the region. Moreover, the livelihood of significant proportion of the Mongolian population as nomadic herders is directly dependent on weather patterns. More than 70% of annual precipitation of Mongolia falls in summer (Yatagai and Yasunari 1994; Dagvadorj et al. 2014), and changes in amount, intensity and type of precipitation affect the agrarian economy and nomadic livestock husbandry of Mongolia (Dagvadorj et al. 2014). A number of research articles and reports on climate change have documented the changes in the annual air temperature, mean annual precipitation and number of extreme events in Mongolia (Batima et al. 2005; Endo et al. 2006; Nandintsetseg et al. 2007; Dagvadorj et al. 2014).

There are a few studies on the changes of summer season rainfall amount and intensity for Mongolia. Yatagai and Yasunari (1994) and Endo et al. (2006) examined these rain characteristics for the period of 1951–1990 and 1960–1998, respectively. According to the study by Endo et al. (2006), the heavy rain frequency in the south-eastern and eastern Mongolia has increased. Marin (2010) reported an increase in spatially very patchy and intense rain, based on the observations of herders. Recently, Goulden et al. (2016) reported a similar trend for the increasing convective rains by several lines of evidence for northern Mongolia, including herder interviews, high resolution rainfall data and thunderstorm activity that were used to hind-cast short heavy rains. It is apparent that more recent and quantitative data need to be included in such analyses looking at changes in precipitation patterns and their effects on landscape ecohydrology. This is because the fluctuations in precipitation and rain intensity are important precursors for desertification, soil erosion and other forms of land degradation that result from flooding, run-off, soil movement, drought and other factors for Mongolia (IG/EIC 2014; Eckert et al. 2015; Vandandorj et al. 2015). Moderate rains are better absorbed into the soil and make up available moisture for plant growth, while the same amount of rain falling in a short period, due to its force, may bring flooding and surface run-off, transporting and eroding the surface soil. Therefore, the water is not soaked into soil, which could be much drier in the end of the day compared to periods following light rain events (Trenberth 2011).

Most of the analyses of climate change in Mongolia focused on the temperature and the total amount of precipitation. To best of our knowledge, no study has so far closely looked at the changes in types, duration and number of rains for summer season based on start-to-end time of all rain events for Mongolia as a whole because data needed for such analyses were made possible only by us for the first time from a paper-based archival format. Therefore, by the present study, we attempt to contribute to the study of climate change in Mongolia by looking at the changes of (1) *summer season precipitation amount and air temperature*, more importantly, (2) *the number and duration of two types of rain (stratiform and convective rain) events*, which are analysed for the first time for Mongolia. In addition, we investigate (3) *the association among these variables* for the summer seasons in Mongolia for the period of 1981–2014.

Data and methods

Daily precipitation, starting and ending time and characters (types) of rain events recorded during the summer seasons (from June to August) between 1981 and 2014 from 55 meteorological stations over Mongolia are the primary data for this study (Fig. 1, Supplementary Table 1). In addition to precipitation and rain event data, temperature data for the same time period from the same stations are used. The only station with shorter series of meteorological data is Darkhan station, which had a record from 1984 to 2014. All these data have been collected at the meteorological stations over Mongolia that are operated by the National Agency for Meteorology and Environmental Monitoring (NAMEM) in Mongolia. The precipitation and temperature data have been used widely for climate change studies and reports for Mongolia, but not the number and duration of different types of rain events as the earlier data were in paper-based format. Therefore, detailed analyses of rain number and duration were made possible by us as we have

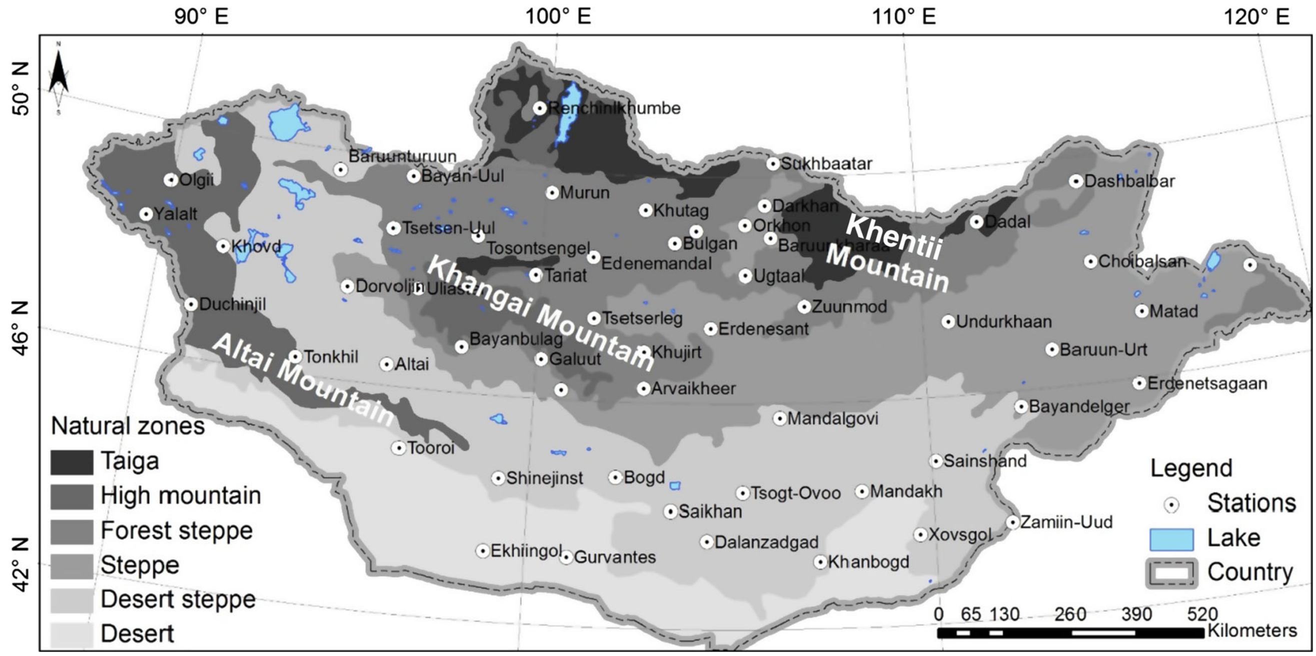

Fig. 1 Locations and geographical distribution of the 55 stations included in the study

digitized the rain event data for the first time for Mongolia. Understanding the pattern of the rain type, number and duration are as important as the studies of precipitation amount trend within the framework of climate change studies.

Meteorologists or observers at local meteorological stations or posts recorded starting time and ending times for all rain events. At the same time, the character and force of the rain were recorded by them according to the guidance from the World Meteorological Organization (WMO; Table 1; Jarraud 2008). There are three characteristics of rains such as showery, intermittent and continuous (Jarraud 2008; Puntsagdorj 2014), which are largely dependent on the cloud type. The showery rain (convective rain) usually falls from cumulonimbus or cumulus clouds, and the intermittent or continuous rain (stratiform rain) is from altostratus and nimbostratus clouds. Within the each rain characteristics, the force of the rain need to be identified during the observation as being heavy, moderate or light.

Generally, cloud forms from an interaction between warm and cold air flows. The warm air mass moves horizontally below cold air masses, as a result very extended (some hundreds of kilometres) cloud called stratus forms at low altitude. This cloud produces stratiform rain and the precipitation characterized by low intensity with long duration and limited vertical extent of rain height, but horizontally covers a huge area (Capsoni et al. 2009). On the other hand, warm air at earth surface tends to move towards to higher layers in atmosphere, where air mass gets cold very quickly and then due to the condensation fast cold downdrafts and warm updrafts take place. This warm and cold air mass flow causes a convective air motion and produces cumulus clouds whose associated rain is often

Table 1 Rain classification according to the WMO guidance and downscaled classification for this study

Guidance by WMO		Downscaling for the study		
Rain character	Rain force	Cloud type	Rain type	Rain force
Showery	Heavy	Cumulonimbus or cumulus	Convective rain	Heavy
	Moderate			
	Light			
Intermittent	Heavy	Mainly altostratus and nimbostratus	Stratiform rain	Moderate + Light
	Moderate			
	Light			
Continuous	Heavy			
	Moderate			
	Light			

characterized by very intense rainfall rates in short duration and covers large vertical, but narrow horizontal area (Capsoni et al. 2009; Lam et al. 2010). In our study, we used the rain characteristics to classify all the rain events into two groups of convective rain and stratiform rain, by integrating intermittent and continuous rain, which is largely based on cloud types (Table 1). The rain forces within the rain characters are not used for the study. But in general, we considered that the force of convective rains is heavy due to shorter duration and higher amount of precipitation than stratiform rain, when the force of stratiform rains is moderate and light because rain intensity is lower compared to convective rains.

Duration of each rain was calculated from the difference of starting and ending time as an observer at a meteorological station records the starting and ending local times of each rain event. Based on these data, total number and duration of convective and stratiform rain events were, respectively, calculated on monthly basis, as well as for the whole summer seasons for 1981–2014. The mean annual summer precipitations and temperatures were calculated based on daily data between 1981 and 2014 (Supplementary Table 1). The temperature means of 55 stations were used to create a map of mean summer temperature in Mongolia (Fig. 2b) using simple technique for incorporating elevation effects in air temperature spatial pattern in ArcGIS 10.1 version. The mean temperature values were first normalized to sea-level equivalents, using the station elevation and a constant linear lapse rate adjustment of -6.0 °C km^{-1}. The adjusted sea-level temperatures were interpolated using the interpolation method of Inverse Distance Weighting (IDW). Finally, the interpolated sea-level temperatures were adjusted back to actual temperatures using the same lapse rate function and a surface of elevation values stored in digital elevation model (DEM). For the mean annual summer precipitations map (Fig. 2a), the ANUSPLIN 4.4.0 package developed by the Australian National University was used. The ANUSPLIN model provides a facility for transparent analysis and interpolation of noisy multi-variate data using thin plate smoothing splines. Generally, the map is a result of attempts to minimize the errors of mean absolute, variance and root-mean-square and to maximize the correlation between the predicted and observed values.

The magnitude of the trend in the time series of rain data was determined using the nonparametric Mann–Kendall test (Mann 1945; Kendall 1975), and the rate of change was evaluated based on the Sen's slope (Sen 1968). The Mann–Kendall test has been used to detect a trend of normally or non-normally distributed time series in environmental sciences, such as changes in hydro-meteorological variables, vegetation phenology and vegetation condition of grasslands (Yue and Hashino 2003; Jain and Kumar 2012; Sayemuzzaman and Jha 2014). The ANOVA was used to identify the differences of precipitation variables among natural zone, and finally, the associations among climatic variables in each station were assessed by the Pearson's correlation coefficient.

Results

Changes in summer precipitation amount and temperature

The spatially interpolated map of mean annual summer rainfall (Fig. 2a) between 1981 and 2014, based on data from 55 meteorological stations, shows that the mean annual summer precipitation amount varies between less than 50 mm in south-western part, especially in the Gobi desert along the south of the Altai mountain range to about 300 mm in the forest steppe in north or north-eastern parts of the country. To be precise, for the last 34 years, the Ekhiin gol and Dadal stations received the smallest (32.7 ± 4.6 mm) and the highest (279.5 ± 16.1 mm) amounts of mean annual summer precipitation, respectively. During this period, the total amount of mean rainfall amount has not changed significantly in majority of the stations in Mongolia. Only significant decreases were observed at Erdenemandal, Tsetserleg and Erdenesant stations in central Mongolia and Ulgii station in western Mongolia. Generally, the summer precipitation amount tends to decrease as the mean annual summer precipitation amount increases (amount of change in summer precipitation vs. mean annual precipitation: $r = 0.44$, $P < 0.01$). This pattern is also visible from the map in Fig. 2a, where the most stations with less than 100 mm rainfall for summer months experienced less than 10 mm rainfall decrease per decade, while most of the stations with more than 100 mm of summer rainfall had drops of more than 10 mm. Interestingly, the decreases of 10–24 mm rainfall per decade occurred between the latitudes of 46°N and 50°N, and the only four stations with statistically significant decreases in summer mean rainfall were found in this range. In contrary, a relatively few stations mostly in the south of big mountain ranges such as Khangai and Altai mountains experienced non-significant increases of summer rainfall amounts. Also, similar non-significant increases were found in the eastern steppe (Fig. 2a).

In terms of summer average temperature (Fig. 2b), Tariat was the coolest station with 11.7 ± 0.23 °C of mean summer temperature, while Ekhiin gol station experienced the hottest mean summer temperature averaged at 25.7 ± 0.15 °C for the study period, among the stations included in this study. The summer average temperature significantly increased across Mongolia, and the average rise in summer temperature for the country was 2.5 °C for

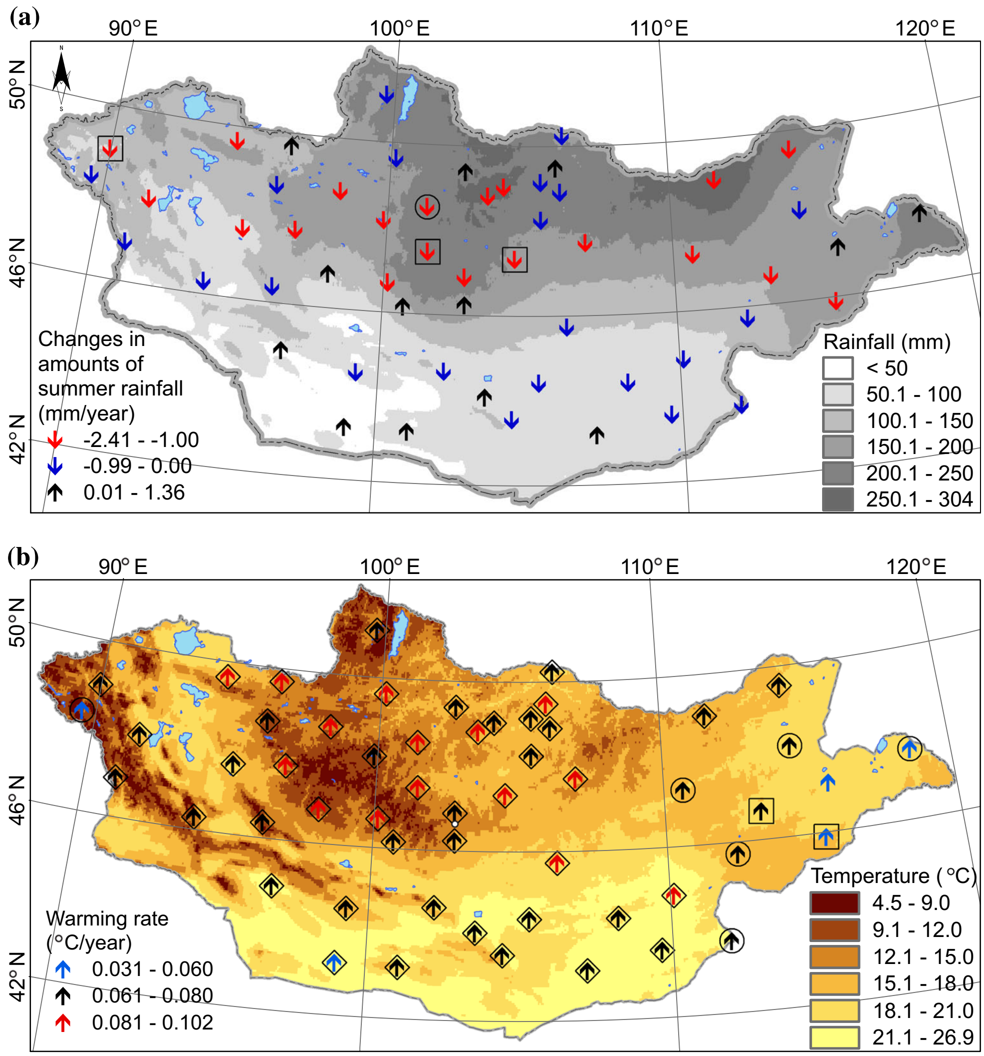

Fig. 2 Geographical distribution and changes of total rainfall **a** and mean temperature **b** in summer season between 1981 and 2014. The *arrows* show the direction of changes in those variables, and the frames indicate statistical significances: *diamonds* $P < 0.001$, the *circles* $P < 0.01$ and the *quadrats* $P < 0.05$

the past 34 years. Comparatively low warming rates were observed mostly at far eastern stations, but still two out of three had significant increasing trends and the only station with non-significant rise in summer average temperature was the Matad station. Even though the station has already reached 1.05 °C warming for the study period, it is considered the weakest warming rate among the 55 stations for the country. Most of the stations along the Altai mountain range, in the Gobi desert and desert steppe in southern part of the country, as well as north-eastern steppe, Selenge river basin and Khangai mountain range have shown 2.0–2.72 °C warming. The large increases (more than 0.081 °C $year^{-1}$ or >2.75 °C total increases) mostly took place in the surrounding area of Khangai mountain region and in northern Mongolia. But more than 3.0 °C increases for the study period were observed in spatially unevenly scattered stations located at Sainshand, Galuut, Baruunturuun, Tosontsengel, Murun and Darkhan.

Characteristics of stratiform and convective rains in different natural zones

The forest steppe has a total of about 100 rain events, which cumulatively continue for more than 130 h throughout a summer (Fig. 3a, b), and the stratiform rains make up about 63% of the total rain events, which continue for 106 h or make up 81% of total rain duration in the forest steppe of Mongolia (Fig. 3). This is the highest number of stratiform rain events followed by high mountain zone. Even though the difference between these two natural zones in the number of stratiform rain events was not statistically significant, the duration of stratiform rains

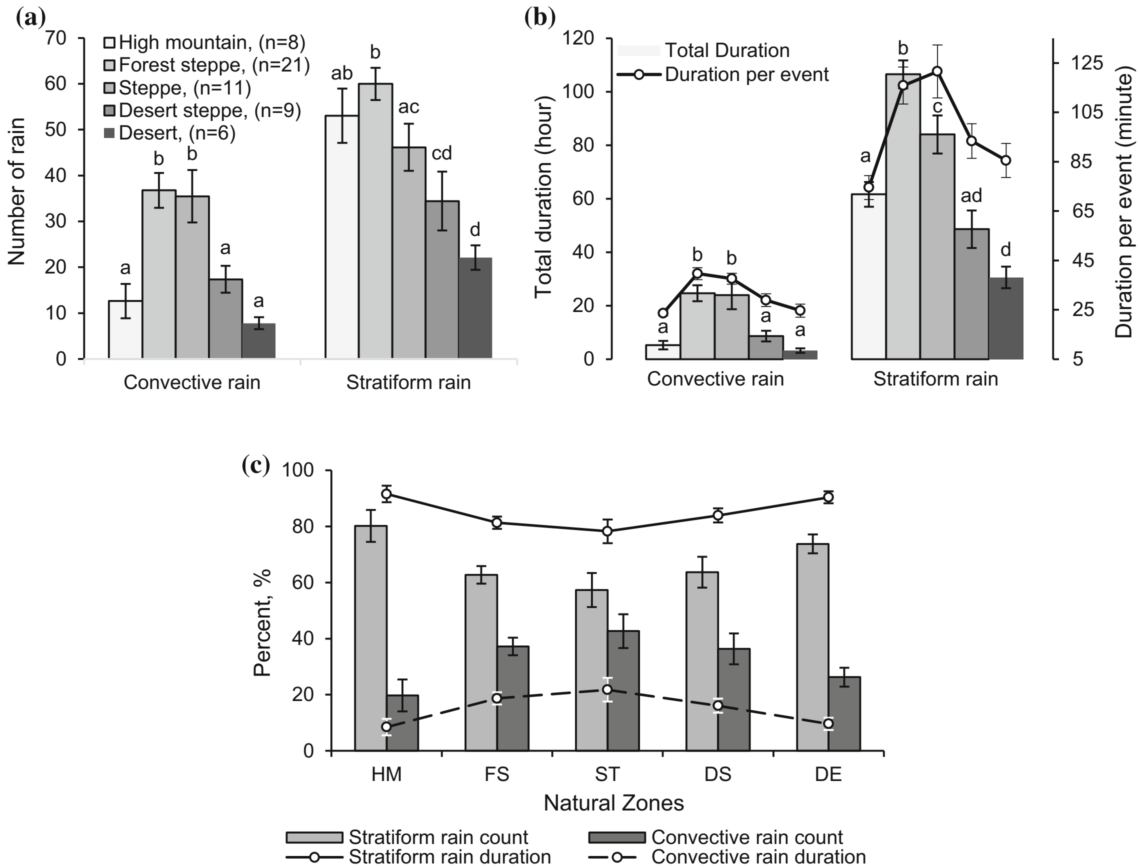

Fig. 3 Long-term **a** mean number, **b** duration and **c** their respective percentage of convective and stratiform rain events of summer in natural zones of Mongolia (1981–2014)

was longest in the high mountain zone, followed by the steppe zone.

For the convective rain event number and duration, the forest steppe is not significantly different from the steppe zone: both with 35–37 rain events and approximately 24 h of duration. However, the forest steppe was significantly different from the other three natural zones that received 8–17 convective rain events totally continuing for only 3–8.6 h for a summer (Fig. 3a, b).

The average duration per rain event is almost the same in the forest steppe and steppe zone with about 40 min for a convective rain and roughly 120 min for a stratiform rain (line graphs in Fig. 3b). The high mountain zone has shortest duration of rains compared to others. In particular, the average duration per stratiform rain in this natural zone is about 75 min.

The number of convective rain events makes up 20 to 43% of total number (Fig. 3c), depending on the natural zones. This is roughly two times as high as the percentage of convective rain duration in the corresponding natural zones. Both percentages of the convective rain duration and number (Fig. 3c) reveal that the steppe zone is more likely to receive convective rains rather than stratiform rains compared to other natural zones, even though the total duration (hours) and number of convective rain events are almost same as those in the forest steppe zone. Approximately 74–80% of total rain number and 90–92% of total rain duration belong to stratiform rains in the high mountain and desert zones.

Changes in number and duration of summer rain events

Total duration and number of stratiform rains in summer months significantly decreased over the majority of the Mongolian territory for the last 34 years (Fig. 4a). The largest drop in this type of rain events and duration were observed around the Khangai mountain range, especially in areas north of this mountain range, as well as in the southeastern part of the country. In contrary, many of the stations in those regions also experienced significant increasing trends of different rates in the number and duration of convective rains (Fig. 4b). Interestingly, mostly non-significant decreases in both rain types were observed along the Altai mountain range in south-western part of the country and the region of Selenge river basin in northern Mongolia.

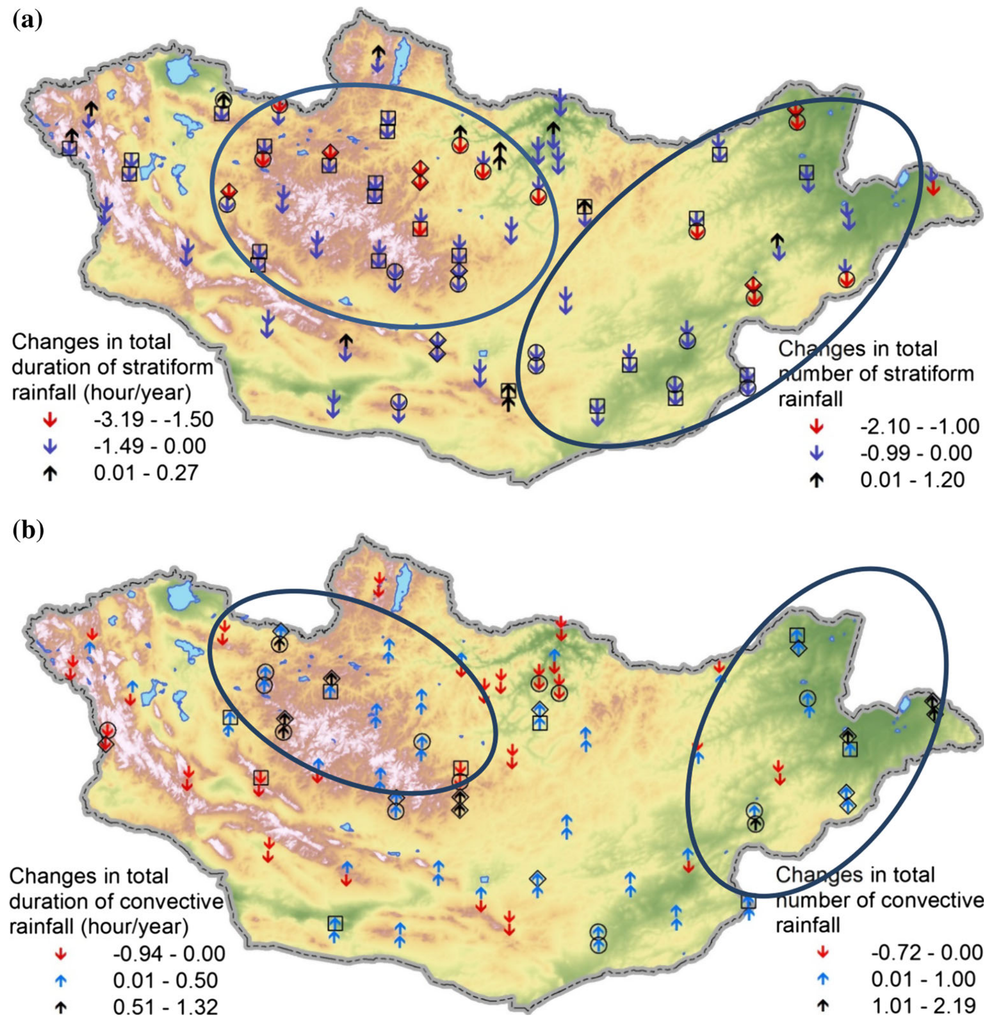

Fig. 4 Changes in the number (*top arrow* of the pair shown for each station) and duration (*bottom arrow*) of summer **a** stratiform and **b** convective rain events. The *arrows* indicate the direction of changes in the number and duration of these rain types. The *colour* of the *arrows* shows the rate of changes and the *frames of the arrows* indicate their significance: *diamonds* $P < 0.001$, *circles* $P < 0.01$ and *quadrats* $P < 0.05$. *Ellipses* highlight regions of opposing trends in stratiform and convective rain events for Khangai mountain range and eastern Mongolia

Association among climatic variables in relation to rain type

The numbers of stratiform rains (column 1 in Table 2), convective rains (column 2) and the total number of rains (column 3) were highly correlated with the duration these respective rain types (Table 2; Fig. 5). However, the duration of rains was more strongly correlated with the total amount of precipitation than their number, in particular for stratiform rains (columns 8–9). For the convective rains, their contribution to the amount of total precipitation was not as high as stratiform rains (columns 8–11). This pattern could also be observed on the total number of rain events and duration too (columns 4–7).

Furthermore, there were negative correlations between the air temperature and number or duration of stratiform rains, especially in the steppe zone, followed by the desert steppe and forest steppe zones (column 13). The relationship between air temperature and convective rains was not consistent. In some stations, the correlation was negative (columns 14–15 for minimum figures), while sometimes it was positive (columns 14–15 for maximum figures). Also, an overall negative correlation between air temperature and precipitation amount was found (column 16).

Discussion

According to a recent report, the average annual air temperature increased by 2.14 °C, while the mean annual precipitation did not change significantly for the last 70 years in Mongolia, except for slight decreases in some open areas including the steppe zone (Dagvadorj et al. 2014). Our study suggests that in the second half of this 70-year period or in the last 34 years, the summer average temperature increased by 2.5 °C for the country ranging from 1.05 to 3.18 °C in different areas. This indicates an accelerating warming trend in summer season for a shorter period, and it is remarkably higher rate compared to the increase in the global mean annual temperature. In terms of precipitation amount, only three stations in central and one station in western Mongolia had a significant decreasing

Table 2 Maximum, average and minimum correlation coefficients between climatic variables in the stations by main natural zones

	Natural zones	1 N-St D-St	2 N-Co D-Co	3 N-Tot D-Tot	4 N-St N-Tot	5 N-Co	6 D-St D-Tot	7 D-Co	8 N-St Prec	9 D-St	10 N-Co	11 D-Co	12 N-St Temp	13 D-St	14 N-Co	15 D-Co	16 Prec Temp
Maximum	High mountain	**0.81**	**0.97**	**0.80**	**0.96**	**0.81**	**1.00**	**0.46**	**0.83**	**0.81**	**0.44**	0.39	−0.10	−0.12	0.13	0.14	0.02
	Forest steppe	**0.79**	**0.95**	**0.80**	**0.97**	**0.87**	**1.00**	**0.73**	**0.59**	**0.80**	**0.64**	**0.63**	0.08	−0.23	0.26	0.14	0.01
	Steppe	**0.89**	**0.95**	**0.84**	**0.96**	**0.82**	**0.99**	**0.53**	**0.65**	**0.89**	**0.53**	**0.69**	−0.22	**−0.47**	0.37	0.27	**−0.46**
	Desert steppe	**0.81**	**0.91**	**0.80**	**0.99**	**0.89**	**1.00**	**0.62**	**0.56**	**0.67**	**0.44**	**0.59**	0.13	−0.29	0.28	0.03	−0.26
	Desert	**0.70**	**0.93**	**0.73**	**0.93**	**0.78**	**1.00**	**0.55**	**0.52**	**0.74**	**0.57**	**0.72**	−0.10	−0.35	0.34	0.22	−0.09
Average	High mountain	**0.61**	**0.91**	**0.59**	**0.86**	**0.49**	**0.97**	0.20	**0.44**	**0.66**	0.12	0.17	−0.34	−0.35	−0.13	−0.14	−0.32
	Forest steppe	**0.63**	**0.80**	**0.55**	**0.68**	**0.52**	**0.92**	0.34	0.36	**0.65**	0.19	0.27	−0.28	**−0.52**	−0.08	−0.25	−0.42
	Steppe	**0.71**	**0.82**	**0.63**	**0.64**	**0.53**	**0.93**	0.28	0.41	**0.71**	0.27	*0.33*	**−0.49**	**−0.62**	−0.06	−0.11	**−0.59**
	Desert steppe	**0.63**	**0.77**	**0.49**	**0.74**	**0.46**	**0.97**	0.23	0.34	**0.60**	0.24	0.35	**−0.46**	**−0.58**	0.07	−0.13	−0.42
	Desert	**0.54**	**0.76**	**0.49**	**0.79**	**0.61**	**0.98**	0.24	0.36	**0.64**	*0.31*	0.34	−0.36	**−0.44**	−0.04	−0.12	−0.24
Minimum	High mountain	*0.33*	**0.71**	0.42	**0.71**	0.22	**0.93**	−0.02	0.01	**0.47**	−0.27	−0.16	**−0.61**	**−0.50**	**−0.48**	**−0.45**	**−0.59**
	Forest steppe	0.41	**0.59**	−0.04	0.04	−0.14	**0.73**	−0.10	−0.08	0.38	−0.16	−0.20	**−0.56**	**−0.76**	**−0.53**	**−0.66**	**−0.65**
	Steppe	**0.51**	**0.66**	**0.46**	*0.31*	0.08	**0.75**	−0.21	0.21	**0.48**	−0.01	0.01	**−0.73**	**−0.72**	**−0.56**	**−0.54**	**−0.71**
	Desert steppe	0.43	**0.68**	0.11	0.18	−0.02	**0.94**	−0.01	0.07	**0.51**	−0.06	−0.03	**−0.75**	**−0.72**	−0.13	*−0.33*	**−0.57**
	Desert	0.27	**0.59**	0.26	**0.56**	0.43	**0.96**	0.11	0.22	**0.50**	0.16	0.14	**−0.60**	**−0.53**	*−0.30*	−0.36	*−0.31*

N Number, *D* Duration, *St* Stratiform rain, *Co* Convective rain, *Tot* Total rain, *Prec* Precipitation and *Temp* Temperature

The indication of significances: bolds $P < 0.01$, underlines $P < 0.05$ and italics $P < 0.1$

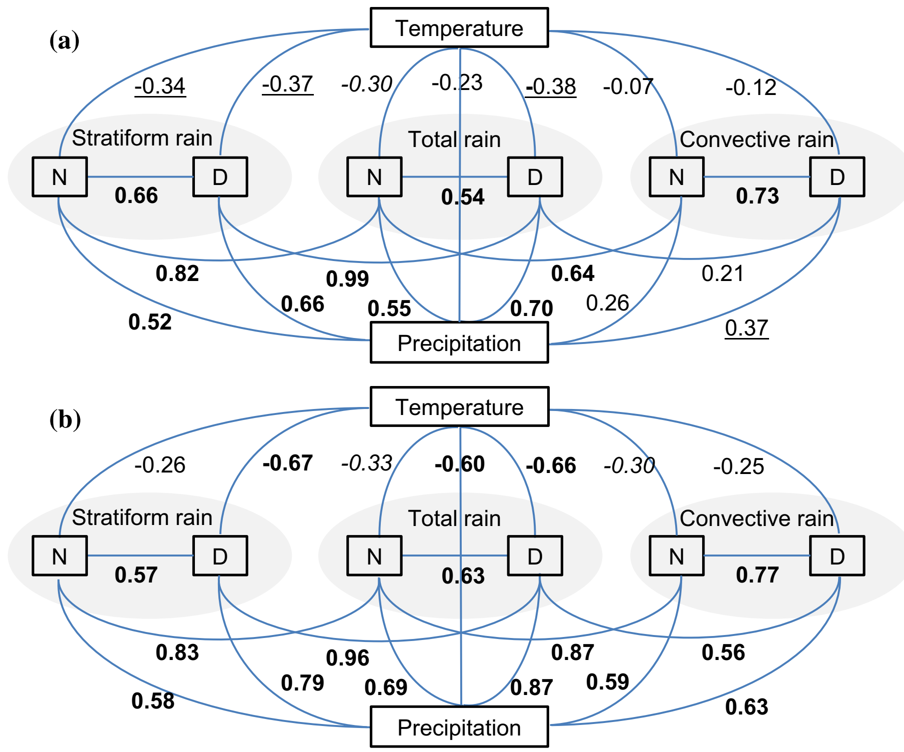

Fig. 5 Examples of correlations between the climate variables shown here for **a** Ekhiin gol (lowest summerly rainfall 32.8 mm for the period of 1981 and 2014) and **b** Dadal (highest summerly rainfall with 279.6 mm for the period of 1981 and 2014) stations. The indication of significances: *bolds* $P < 0.01$, *underlines* $P < 0.05$ and *italics* $P < 0.1$

trend of summer season rain amount. More interestingly, considerable changes were found in the type, number and duration of these rain events.

Endo et al. (2006) reported that the weaker rainfall events became dominant in the northern part of central Mongolia and the frequency of relatively heavy rainfall events increased in eastern and southern areas. But our results suggest that the stratiform or probably weak rains did not become dominant in that region (northern part of central Mongolia). Stratiform rains were initially very common across the country, and this type of rains makes up about more than 60% of total rain events and contributes at least 80% of total rain duration in any of five ecological zones. The total number and duration of stratiform rains per summer significantly decreased around the Khangai mountain in central Mongolia and in the south-eastern and eastern steppe areas. Mostly non-significant decreases were observed for the rest of the country. In contrary, our results are in line with Endo et al.'s (2006) results on the increase in convective or probably heavy rain frequency in the south-eastern and eastern Mongolia. In addition, the duration of this type of rains also increased significantly in the same areas: it is not only happening in eastern and south-eastern parts of the country, but also clearly observed around Khangai mountain range in central Mongolia.

Marin (2010) reported several key changes in precipitation based on observation by local herders in Mongolia. For instance, the rains have become more intense and less effective for vegetation due to run-off. Rains also have become spatially very patchy, a phenomenon called 'silk embroidery rains' among the public and summer rains have become delayed. These changes in rain characters that herders observed are referring to the increase in convective rains with mostly very intense rainfall rates in short duration of time and cover limited horizontal area (Capsoni et al. 2009). In a recent study, Goulden et al. (2016) reported a similar trend for the increasing convective rains by several lines of evidence for northern Mongolia, including herder interviews, high resolution rainfall data and thunderstorm activity that were used to hind-cast short heavy rains. Moreover, researchers have reported massive decreases in light rains, decreases in the number of long duration rain events (≥3 days) and decreases in the number of rainy days, while some increase in rain intensity was observed in neighbouring countries, particularly in China (Gong et al. 2004; Zhai et al. 2005; Liu et al. 2011). Also, globally, there are strong positive correlations between air temperature and rainfall intensities, especially for convective rains (Berg et al. 2013; Westra et al. 2014).

As the stratiform rains contribute major percentage of the total summer rain events and duration, the significant decrease of summer rainfall amount observed at the four stations of Mongolia could be associated with the decrease of stratiform rains, in particular with decrease of their duration because the duration of rain events appears to be more important for the total rainfall amount than their numbers. In spite of non-significant changes in the summer rainfall amounts almost all of Mongolia, the number of summer days with more than 0.1 mm rain has reportedly increased over almost all of Mongolia for the period between 1960 and 1998 (Endo et al. 2006). Probably, this could be explained by the increase in convective rainfall events in majority of the Mongolian territory. Therefore, it can be concluded that the decrease in number and duration of stratiform rains leads to decrease in rainfall amount, while the increase in heavy or convective rainfall number and duration brings the total rainfall amount back to its average. Because convective rains continue for short period of time, the rainfall amount falling in a certain period is always higher than the amount of stratiform rains. It is interesting to investigate the effects of rain type changes on the regional climate, the hydrological cycle and ecosystem functions.

The significant negative correlations between average air temperatures and the numbers or durations of stratiform rains suggest that the stratiform rains effectively alleviate the increase in average air temperature (Fig. 5). The reason is because stratus clouds usually cover a massive area, and the stratiform rains continue for a relatively long period of time (Capsoni et al. 2009), sometimes up to a couple of or more days, which effectively keeps air temperature relatively cool in that particular area for the period of rain. Therefore, the decrease in the number and total duration of stratiform rains allows the sun to heat the land surface longer than before, contributing to further increase in air temperature. Certainly, shifts in rain types are not the main cause of warming, but they could indirectly affect the average local temperature. The increase in summer air temperature intensifies the process of land surface heating and the warm air mass moves to high altitude of the atmosphere more quickly and frequently than before. As a result of this process, the total number of convective rain events and their cumulative duration have increased in central and eastern Mongolia. The increase in convective rainfalls could not exert cooling effect on air temperature effectively by restricting direct sunlight to the land surface, specifically because this type of rain is spatially and temporally very patchy (Marin 2010). The correlation was significantly negative at some stations in the high mountain zone, forest steppe zone and steppe zone, which could be explained by the feedback of increased convective rain frequency and its total duration to air temperature. But this pattern was not consistent. Therefore, the changes in rain types not only affect the air temperature, but also they could contribute to seasonal local average temperature.

More than 60% of annual total precipitation falls in summer in Mongolia (Endo et al. 2006). But from 64 to 96% of the total rainfall is lost to evaporation in case of Selenge river basin in northern central Mongolia, because the country has longer annual average sunshine period with 3000 h than any other countries at the same latitude (Ma et al. 2003). These climatological or geographical characteristics of the country, plus the high rate of increase in summer air temperature and the rain type changes only intensify the water loss through evapotranspiration, which is the main cause of soil moisture decrease all over Mongolia (Sato et al. 2007). Also, the rains in southern Mongolia rely on re-circulated local moisture due to a southern shift of the East Asian Monsoon (Marin 2010). As a result of increased evapotranspiration and air temperature, the soil gets dry and probably the cumulus cloud forms quickly, making convective rainfalls more frequent. But the water input from the intense and short rain events over relatively small areas mostly runs-off and then erodes the soil surface due to lack of infiltration into hot and dry soil, especially where the vegetation is sparse. At the same time, the water quickly evaporates again, probably during the run-off or in a short time after the rain. This makes the water cycle in the ecosystem very short and frequent, but less effective to vegetation growth. Therefore, increased number and duration of convective rain events may adversely affect local ecosystem services, on which the livelihood of nomadic herders is dependent. Due to frequent heavy and short rainfalls, the river water levels can be hugely variable, although we did not specifically relate changes in rain characteristics to river hydrology in the present study.

Mongolian rivers rely heavily on run-off that is generated in mountainous headwater regions (Hülsmann et al. 2015; Minderlein and Menzel 2015; Tsujimura et al. 2007a) and vegetation on mountain slopes uses rain water, while that on river banks mostly use river water (Li et al. 2007). Generally, this implies that the plants dominantly use rain water in different ways: directly and also indirectly via river water. As mentioned above, more than 64% of rain water directly goes to atmosphere by evaporation just after rain in northern Mongolia. It means only a small percentage of total rain water is available for plants, while the vegetation is largely dependent on the precipitation and its annual variation, in particular in steppe and desert steppe zones (Vandandorj et al. 2015). Even though the plants use from this small amount of water from rain and river, the ratio of transpiration to evapotranspiration was estimated to be at 60–73% in a forested site and 35–59% in a grassland site in north-eastern Mongolia (Tsujimura et al. 2007b). It suggests that the plants in northern Mongolia may have another source of water beside rain water and river water, which is mostly charged by rain water. Probably this source could be permafrost or glaciers.

Sharkhuu et al. (2007) found that the increase in the mean annual permafrost temperatures from 0.2 to 0.4 °C per decade and this increase is the one of the several main factors of the degradation of permafrost, which became more intensive since 1990s compared to the previous

15–20 years (1970s and 1980s) in northern Mongolia. Moreover, for the last 30–60 years of the last century, western Mongolian mountains lost 10–30% of their total glacier cover, mostly due to warming (Tsutomu and Gombo 2007). The melted water, however, is used for plant growth; it goes to the atmosphere through transpiration and via evaporation as well, and contributing to the increase of the convective rain frequency that occurs due to heat. At this stage, the warming may have been reducing the dependency of the plant on rain water in the regions with glacier and permafrost, but once this source of the moisture is depleted, dramatic changes may occur for plant community and productivity in that regions.

Conclusions

During the last 34 years, the mean summer air temperature significantly increased by 2.5 °C, ranging from 1.05 to 3.18 °C, for Mongolia. The rate of the warming in summer season is higher than annual rate of warming. For the summer precipitation, no significant changes were observed for the most of the stations, and only significant decreases were found at three stations in central Mongolia and in one station in western Mongolia. More interestingly, remarkable changes were observed in the rain types, their total duration and number of rain events. The number and duration of convective rains have increased, while those of stratiform rain events have decreased in almost all parts of Mongolia. These changes were highly significant around the Khangai mountain area in central Mongolia and south-eastern desert steppe and eastern steppe zones, suggesting a possible transition from stratiform rains to convective rains. These findings imply that increasing temperature and altered rain type ratios affect each other as the decreasing number and duration of stratiform rain events allow for progressively longer sunshine period, possibly feeding back to the increased temperature. The release of this latent heat fuelling the upward movement of lost moisture from the land surface and producing the convective rains could be one of the reasons of the significant increase in convective rain frequency in Mongolia for the study period. These changes lead to an intensification of the regional water cycle by a shift towards short, heavy rains, which provide effectively less water available to plants. Moreover, they tend to increase surface erosion.

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