Biogeosciences Discuss., 9, 11179–11200, 2012
www.biogeosciences-discuss.net/9/11179/2012/
doi:10.5194/bgd-9-11179-2012

Biogeosciences
Discussions

A probe into the different fates of locust swarms in the plains of North America and East Asia

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Received: 31 March 2012 – Accepted: 3 August 2012 – Published: 20 August 2012

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Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Locust swarms had periodically raged in both North American Plains (NAP) and East Asian Plains (EAP) before 1880 AD. After this period, the locust outbreaks almost never recurred in NAP but have continued to occur in EAP. Since large quantities of pesticides were used in the major agriculture regions of NAP in the late 1870s; this has been suggested as a possible major cause of the disappearing of locust outbreaks. Extensive applications of more effective chemical pesticides were also used in the granary regions of EAP in the 1950s in an effort to kill the pests at a much higher intensity. However, locust swarms came back again in many areas of China in the 1960s. Therefore, NAP locust extinction still remains a puzzle. Frequent locust outbreaks in EAP over the past 130 yr may offer clues to probe key control elements in the disappearing of locust outbreaks in NAP.

This paper analyzes the climate extremes and monthly temperature-precipitation combines of NAP and EAP, and found the differences in their frequencies of these climate combines caused different locust fates in the two regions: restrained the locust outbreak in NAP but induced such events in EAP. Validation shows that severer EAP locust outbreak years were coincided with the climate extreme combines years. Thus we suggest that climate changes in frequency, extremes and trends can explain why the fate of the locust plague in EAP was different from that in NAP. The study also points out that, under the present global warming, cautions should be taken to make sure the pest hazard being nipped in the-bud.

1 Introduction

To North Americans, locust plagues during the late 19th century are of historical interest only. Rocky Mountain locust, *Melanopolus spretus*, referred to as *Caloptenus spretus* in the reports of the time was a swarming species that periodically produced plague results in the NAP from at least 1800 AD (Riley et al., 1880; Riegert, 1977).

Typically between 1873 AD and 1877 AD the vast infestations from Canadian Prairies to Missouri devastated crops, starved herds of cattle, ruined state budgets, and drove homesteaders from the land (Hudson Bay Company Archives, 1891; Criddle, 1920). In fact locust swarms were not only plagued in NAP but also in the EAP (Chen, 1935; Ma, 1958). The worst locust plague were concentrated in 1874–1878 AD, with records in history books describing the events as "locust swarms darkened the sky and cleared off grain seedling in the drought summer" in 1876 AD in lower reaches of Yangtze River, and "locust shadowed sunshine; people were starving to death and the bodies on the roads" in 1875 and 1877 AD in lower reaches of Yellow River (Zhang, 2004).

It is fascinating that locust plagues gradually disappeared and almost never recurred in NAP (Lockwood and DeBrey, 1990; Lockwood, 2004; Chapco and Litzenberger, 2004) while in EAP locust swarms have outbroken continuously to the 21st century (Chen, 2000; Wu et al., 2006). The locust outbreaks in western and eastern plains of the Pacific have shown very different outcomes (Fig. 1a). Since chemistry industry in North America developed early, large quantities of pesticides were used in the major agriculture regions of NAP in the late 1870s, which has been suggested as a possible major cause of the disappearing of locust outbreaks (Lockwood, 2004). Comparatively, as chemistry industry developed much later in EAP than NAP, extensive applications of more effective chemical pesticide to kill the pest were conducted at higher intensity in the granary region of China in EAP in the 1950s (Chen, 2000). However, locust swarms in many areas of China came back again in the 1960s (Ma, 1965; Wu et al., 1990). Thus we feel that the uneven treatment of the grassland regions with the arsenic baits available at the time would be unlikely to drive the Rocky Mountain locust to extinction, although population densities and reproduction could be reduced. Frequent outbreaks in the EAP over the past 130 yr offer an important evidence to probe key control elements of the disappearing in the NAP.

The major species caused the locust outbreaks in NAP was *Melanopolus spretus* (Melanoplinae subfamily of Acrididae family) (Criddle, 1920; Lockwood, 2004), although non-swarming species of grasshoppers also exhibited extreme fluctuations in abundance and widespread damage to vegetation. The historically important locust species in EAP has been *Locusta migratoria manilensis* (Oedipodidae subfamily of Acrididae family) (Ma, 1958; Zhang, 1999; Zhang and Kang, 2005). Although locusts in the two regions are from different subfamilies and may differ in endocrinological characteristics related to locust development, both species are herbivorous insects with high rates of reproduction, swarming behavior, tendency to migrate long distances, and severe cereal-devastation. There were at least 12.5 trillion insects with a total weight of 27.5 million tons in 1874 AD (Garcia, 2000), covered an area of 250 million acres (∼ 1.01 million km^2) in the Central US, by entomologists record (Bomar, 2008); which is similar to a fact in EAP that the locust outbreak had a density of more then 2000 locust m^{-2} and covered an area of 1.07 million km^2 in summer of 2001 AD (Huang and Zhu, 2001; Ren and Tang, 2007). These facts enable us to compare both in swarm density and endangering extent.

In terms of the locust ecology and outbreak preconditions, climate strongly influenced the onset and persistence of locust outbreaks, which severe cold winter would kill overwintering eggs, low temperature at growing seasons suppress the insect breeding and reproducing, and higher rainfall and wet condition in spring-summer halt the pest dispersing and migrating (Chen, 1935; Ma, 1958, 1965; Wu et al., 1990, 2006). Combined effects of climate conditions and the extremes may induce or restrain locust outbreaks. Although it is generally believed that changes in pesticide use and land use triggered the demise of the Rocky Mountain locust in NAP (Lockwood, 2004), we feel that it is important to view such hypotheses within the background of climate variability and trends because of their suspected interactions and influence on locust outbreaks in EAP and NAP. Indeed, climates have changed significantly on both sides of the Pacific over the past 130 yr, with extended cooling and warming trends (varying by regions) and increasing in the frequency of extreme weather and climate (IPCC, 2007).

Thus our study took two regions of NAP and EAP together to probe what differences of climate changes have lead to different endings of locust outbreaks during the past 130 yr, by the following approaches: (1) general climate conditions that are hypothesized, based on biology and previous studies, to be locust inducing (warm-dry) or restraining (cold-wet and warm-wet), which are summarized and examined for matches with historical locust outbreak years; (2) restraining combinations of unfavorable climate conditions that likely impacted locust outbreaks biologically and ecologically during the past 130 yr are hypothesized as contributing to locust population decline; and (3) the histories and trends of locust hazards in North America and East Asia are compared with regard to the timing of locust decline and extinction in North America and continued periodic locust population eruptions in China.

2 Data and methods

We took two regions of the Northern American Plains (NAP: 35–55° N and 95–110° W) and the Eastern Asian Plains (EAP: 35–55° N and 110–125° E) in the present study (Fig. 1). The NAP study area includes the provinces of Alberta, Saskatchewan and Manitoba in Canada, and the states of North Dakota, South Dakota, Wyoming, Nebraska, and Kansas in the USA. These key locations have good long-term meteorology station data coverage, and had major locust outbreaks during the 19th century. The EAP study area includes the Northeast China Plain, Northern China Plain, and Middle-low Reaches Plains of the Yangtze River, where locust outbreaks have been documented in historical records and monitored by modern observations. Time series of monthly temperature/precipitation changes were carried out by regional means from 30 meteorology stations in NAP (Environment Canada Canadian, 2005; Vose et al., 2008) and 26 meteorology stations in EAP (National Climate Center of China, 2010) during 1880–2009 AD (Fig. 1). In this paper, we abbreviated the 12 months as 1, 2, ... 12 and the 4 seasons as djf (winter), mam (spring), jja (summer) and son (fall).

2.1 Compilation of NAP locust data

Locust index has been complied based on historical reports and summaries of the locust hazards of the time (Riley et al., 1880; Riegert, 1977; Hudson Bay Company Archives, 1891; Criddle, 1920; Conte, 1877; Dawson, 1876; Packard, 1878; Pillsbury et al., 1876; Riley, 1877), and subsequent reviews and commentaries on the locust in NAP (Criddle et al., 1920; Dempsey, 1973; Riegert, 1980). Severe infestations were noted in Canada from at least 1800 AD, when explorer Alexander Henry reported “grasshoppers piled on the shore of Lake Winnipeg” (Riegert, 1980). In 1818 AD, migrant grasshoppers (primarily the Rocky Mountain locust, *M. spretus*), attacked Lord Selkirk’s colony, “on the 18th of July, 1818 AD, clouds of grasshoppers settled down on the colony and ate up every green thing” and in 1819 AD, the colony was “threatened with starvation” indicated by other reports. Some reports also included the damage caused by non-swarming species of grasshoppers, mainly *Melanoplus sanguinipes* and *Camnula pellucida*, which are still common outbreak pests in the region (Johnson, 1989). Wide-spread damage by Rocky Mountain locust swarms was confirmed and reported in Western Canada in 1800, 1818–1819, 1848, 1857–1858, 1864–1865, 1867, 1869–1870 and 1872 AD, and especially in 1874–1877 AD (Dawson, 1876); similar events were also noted in abundance from Missouri to the Canadian border during the same years (Dawson, 1876; Packard, 1878; Pillsbury et al., 1878). The swarms devastated both agriculture and natural ecosystems. Journalist Henri Julien, accompanying the Northwest Mounted Police (NWMP) in the western territories, documented infestations of 16 July 1874, and noted in his diary: “seeing them at work, as I did, with the modes of attack and the clean sweep of devastation which they carry on, I can form some idea of the locust plagues of ancient Egypt” (Julien, 1989). Private Fred Bagley, accompanying Major James Macleod of the NWMP, recorded seeing at dawn on 12 July 1874 AD that the grasshoppers (Rocky Mountain locusts) covered the landscape, where he also saw the shape of a sleeping sentry, entirely covered with grasshoppers and holding a carbine that was a thick mat of the insects (Cruise and Griffiths, 1997).

His diary for that day notes “Grasshoppers so numerous that they darken the sun. Every step we take through the grass disturbs thousands of them”. Vitalin Grandin, the Oblate Bishop of St. Albert, traveling with the NWMP to visit missions in Southern Prairie Canada wrote that in 1876 the “soil looked rich and fertile, but the grasshoppers destroy everything growing on the soil. Beginning at the Red Deer River, down to this place and even as far as Benton, there reigns real devastation” (Dempsey, 1973). The swarms often also extended into the eastern portion of the Canadian Prairies, not only swarming, but also breeding.

Thus based on historical reports and summaries of the locust hazards of the time, NAP locust outbreak index is rated on a 0–3 scale, with 0 indicating no reports of major infestations, and 3 being most severe with widespread devastation (Fig. 1a).

2.2 Compilation of EAP yearly locust series

Annual records of EAP locust outbreaks (Fig. 1a) were sourced from two types of data. Data in the period of 1850–1958 AD is annual locust index that was sourced from Chinese historical literatures, compiled by Ma (1958) and tide up by Yu et al. (2009). The annual locust index is rated in relative severity from 0 (no locust outbreak) to 10 (most severe). Locust data after 1958 AD were originated from the observed locust stricken areas in China. The data of 1949–1999 were compiled by Wu et al. (2006), and the data after 1999 were compiled, as part of the present study, from the locust stricken area based upon *Statistics Annals of Agriculture in China* (China Ministry of Agriculture, 2009). The original annual locust stricken area data were in the unit of square kilometer (km^2). To consistent with Ma’s 10-class locust index, we rated the 1949–2009 AD series into 10 classes by each 10 percentile cutting-off at the 5th, 15th, . . . 95th of the area values (Fig. 2a). Quality checking for the overlapped period of 1949–1958 AD between the locust index and the ranked locust stricken area shows that the two series are significantly correlated (Fig. 2b).

2.3 Comparison analysis for two regions

Analysis for frequency differences:

Extremes of temperature and precipitation can be combined into four models: warm-wet, warm-dry, cold-wet and cold-dry combinations. We applied a cut-off > 50th, 60th, ... 90th percentiles in temperature or precipitation for the extremes of warm or wet climate, and a cut-off < 10th, 20th, ... 50th percentiles in temperature or precipitation for the extremes of cold or dry climate. Frequency analysis of the climate extremes was carried out by establishing two-direction models of "hazard-restraint climate" vs. "hazard-induced climate". According to biology and ecology of the locust outbreaks (e.g. reviews in Ma, 1965; Wu et al., 1990, 2006; Chen, 2000; and a compilation in Yu et al., 2009), the restraint model is looking for cold-wet extreme combinations and the induced mode for warm-dry combinations, although other two models of cold-dry and warm-wet combinations were also examined. We searched for significant differences of the frequencies between NAP and EAP, by running the models of two regions, respectively, including 7225 matrix, i.e. $(17 \times 5) \times (17 \times 5)$ by 17 climate variables (12 months, 4 seasons and 1 annual) and 5 percentile series (> 50th or < 50th percentiles with 10 percentile interval), both for changes of temperature (ΔT) and precipitation (ΔP).

Analysis of the trend and probability:

To examine the different trends of climate in NAP and EAP, Mann-Kendal trend tests (Kendall 1975; Hirsch and Slack 1984; Gilbert, 1987) were undertaken in two regional climate series of NAP and EAP. We firstly compared climate trends of the two regions, and then checked the EAP climate trends with EAP locust years.

Finally in order to check if extreme climate combines increases their occurrences in EAP more than that in NAP, we did extreme probability analysis. Gumbel probability well represents extreme values and estimates the probability distribution in the population (Gumbel, 1954; Nadarajah, 2006). To estimate parameters location (μ) and scale (σ) in Gumbel (X, μ, σ) distribution, the observations of time series of monthly temperature and precipitation ($X = \Delta T_i$ or ΔP_i, where i is month from January to December) for the NAP and EAP during 1880–2009 AD were calculated using Maximum Likelihood Estimation method (Ritzema, 1994). To reduce sampling uncertainty, variate ΔT and ΔP were generated by 10 000-random sampling, following the Gumbel distribution. The patterns of the temperature and precipitation extremes were checked by 2-D-scatter diagrams. The data processing and matrix manipulation were conducted by using FORTRAN programs.

3 Results

3.1 Difference of frequencies

Frequency analysis has detected the most significant differences of temperature/precipitation between NAP and EAP: the cold-wet extremes at combinations of $\Delta T < 30$th and $\Delta P > 80$th percentiles are 4.5–6.5 times higher in NAP than EAP, focused on colder spring-summer months with wetter spring-summer months (Fig. 3a). This suggests that during the restraint years for locust outbreaks, lower winter temperatures with higher summer or higher annual precipitations were more likely to occur in NAP than in EAP. In fact, among the severe pest outbreak years (taking > 4 class in the 0–10 scale) since 1850 AD in EAP, within total 26 yr of the cold-wet combination, only 3 yr of locust outbreak, i.e. 23 yr with no locust outbreaks (brown dots in Fig. 3b). The 88.5 % chance suggests that such extreme combination years did restrain most of the locust swarms.

In contrary, the most significant differences of temperature/precipitation between NAP and EAP occur in the dry-warm extremes at $\Delta T > 70$th and $\Delta P < 30$th combines: 1.8–3.1 times higher in EAP than NAP, focused on warm winter and warm spring-summer with dry growing season (Fig. 3c). Actually, within total 37 warm-dry extreme years in EAP, the locust outbreaks occurred in 26 yr (red dots in Fig. 3d), indicating favorite impacts of 70 % chance. This suggests that higher winter and spring-summer temperatures with drier spring-summer that normally inducing locust outbreaks were more likely to occur in EAP than in NAP.

We also calculated the frequency and matches of warm and wet conditions in EAP and NAP, with the combination of $T > 30$th and $P > 80$th percentiles. This combination is hypothesized to be conducive to natural control by pathogens, although other mechanisms, such as slowed development and feeding rates, may also operate under wet conditions. The ratio of the warm-wet years with locusts (the matching years) to warm-wet years without locusts (non-matching years) in EAP was 6:50 during a total of 56 yr of the severe locust outbreaks. This suggests that although there was a higher frequency of warm and wet years in EAP than in NAP, the warm-wet years did not favor locust outbreaks in the EAP.

3.2 Probability analysis

Examination of extremes of climate series was performed by Gumbel probability analysis, which showed significant differences of the extreme value patterns of NAP from EAP, in plotting 2-D-scatter diagrams of Gumbel-distributed temperature/precipitation extremes for 1880–2009 AD series (Fig. 4).

In diagrams of extreme patterns of higher winter temperature changes ($\Delta T\mathrm{djf} > 70$th percentiles) with lower annual precipitation changes ($\Delta P\mathrm{ann} < 30$th percentiles), we found that positive extreme values of $\Delta T\mathrm{djf}$ and negative extreme values of $\Delta P\mathrm{ann}$ in NAP (Fig. 4a) are much lower than that in EAP (Fig. 4b) ($p < 0.01$). The critical values of $\Delta T\mathrm{djf} > 90$th percentiles in NAP and EAP are +4 °C and +6 °C respectively, and $\Delta T\mathrm{mam} > 6\,^{\circ}\mathrm{C}$ in the two regions are 13.0 % and 35.9 %, respectively (Fig. 4 a1, b1). The critical values of $\Delta P\mathrm{jja} < 10$th percentiles in NAP and EAP are −17 mm and −303 mm, respectively, and $\Delta P\mathrm{jja} < -20\,\mathrm{mm}$ in the two regions are 7.20 % and 19.15 %, respectively (Fig. 4 a2, b2). This suggests that years with winter warm-annual dry extremes, a climate which favors the overwintering locust eggs, occurred with a probability of 2 ~ 3 times higher in EAP than that in NAP.

We also check the extreme patterns in different seasons: higher spring temperature changes (ΔTmam > 70th) with lower summer precipitation changes (ΔPjja < 30th) (Fig. 4c and 4d). It shows that positive extreme values of ΔTmam and negative extreme values of ΔPjja in NAP (Fig. 4c) are much lower in NAP than that in EAP (Fig. 4d) ($p < 0.01$). The critical values of ΔTmam > 90th percentiles in NAP and EAP are +2 °C and +6 °C, respectively, and ΔTmam > 6 °C in the two regions are 7.3 % and 24.9 %, respectively (Fig. 4 c1, d1). The critical values of ΔPjja < 10th percentiles in NAP and EAP are −43 mm and −103 mm, respectively, and ΔPjja < −50 mm in the two regions are 7.0 % and 27.5 %, respectively (Fig. 4 c2, d2). The analysis provided results of climate extreme change differentiated in EAP from NAP: years with spring warm-summer dry extremes that favor locust multiplying and swarm dispersing, occurred with a probability of 3.5 ~ 4 times higher in EAP than that in NAP.

3.3 Trend analysis

The M-K trend analyses indicate that, for the period of 1880–2009 AD, the temperatures in January–February, July, winter, spring and summer, and precipitation in spring in NAP all increased significantly ($p < 0.05$) (Fig. 1b). For the same period, the EAP temperatures in January–February, April–May, winter, spring and summer, and precipitations in May and spring in EAP also increased significantly ($p < 0.05$), with general trends of increased winter and spring temperature and decreased summer precipitation since 1950 (Fig. 1c).

Here, we applied climate data since 1840 AD from Beijing meteorology station, one of the longest climate records in EAP, for validation of the locust outbreaks responded to trends of the climate change. The M-K test for the time series shows the trend change is significant ($p < 0.05$) for temperatures of January–February, April, winter and spring, and precipitations of July and summer. The climatic trend at Beijing is almost the same as that of the EAP, showing generally temperature increasing in spring but precipitation decreasing in summer (Fig. 5). Correlation analyses showed significantly positive correlations of EAP locust index with the temperature changes in January, February, April, winter and spring (R +0.37, 0.42, 0.46, 0.44 and 0.36 respectively, $p < 0.05$), and negative correlations with the precipitation changes in July and summer (R −0.38 and −0.3, $p < 0.05$). The results confirmed that both localized and regional trends of climate change were in favor of plagues in the 20th century in EAP.

4 Discussion and summary

As we have noted, there have been a number of previous explanations for the disappearance of the Rocky Mountain locust in NAP, including large-scale pesticide application and conversion of natural grassland into industrialized farmland and agriculture, often including a change from grass to alfalfa (see a summary by Lookwood, 2004). However, climate changing trends and climate variability has been significantly different in NAP from EAP during the past hundred years, and could be a critical part of the factors of climate extreme combination causing the loss of this species. Our study found the frequency of the combination of lower temperature in January and February (the egg overwintering season for locust) and higher precipitation in summer and January–December in NAP to be 4.5–5.0 times higher than that in EAP. Also, the frequency of the combination of lower temperature in March–August (the growing season for the locust) and higher precipitation in summer and January–December in NAP was 5.5–6.0 times higher than that of EAP. By contrast, the frequency of climate combinations of higher temperature in January–February and lower precipitation in April–June and January–December, EAP is 2.3–3.1 times higher than that in NAP. The combination of cold winter and low temperature during the growing season and higher precipitation in spring and summer in NAP greatly restrained locust outbreaks, and may have contributed to their decline and extinction soon after 1900 AD. As noted by Lockwood (2004), habitat modification and agricultural changes in vegetation may have been the final blow to locusts in the NAP; it seems likely that a series of years of unfavorable climate change put them at a low and vulnerable state, making way for extinction, as opposed to events in the EAP.

Existing studies indicate that winter temperatures in both North America and East Asia have increased over the past century (Zhao, 2005; IPCC, 2007). However, the temperature increase in Eastern China was particularly significant and reached +0.49 °C/10 yr (Ren and Guo, 2005). Studies also show the frequency of storms has increased, while weak precipitation is significantly decreasing in North America and many regions of the world (Thomas et al., 1998; Gutowski et al., 2007). By contrast, the frequency of weak precipitation has increased in China since the beginning of the 20th century; hence drought has also increased (Ma et al., 1996; Liu and Ding, 2010). The characteristics of large-scale changes in regional temperature and precipitation coincide with the results regarding extreme climate and their characteristic assemblages, and could help to explain the different fates of the locust outbreaks in the two regions.

Differences between EAP and NAP in changes in precipitation and temperature in the current century could be related to the adjustment and reorganizing of atmospheric circulation of the two continents (Allan and Soden, 2008). Precipitation and temperature changes in Northern China were implicated as an explanation for recent Oriental migratory locust outbreaks in the Huanghe River and Huaihe River regions, which have occurred mostly 1 to 2 yr after El Niño events (Zhang and Li, 1999), while combination changes in temperature and precipitation did impact on the locust swarms for thousand years in China (Stige et al., 2007; Yu et al., 2009). Although the locust in North America is now extinct, the threat of related grasshoppers to rangeland and cropland still exists (Lockwood et al., 1995), though many grasshopper species are not agricultural pests (Johnson, 2008). Current and future warming trends are expected to increase the frequency, severity and duration of outbreaks of some of the species remaining in NAP, and cautions should be taken to make sure the pest hazard being nipped in the-bud.

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Acknowledgements. Financial support for this research was provided by Global Change Research Program of Ministry of Science and Technology of China (2012CB956103), International Partnership Program and External Cooperation Program of Chinese Academy of Sciences (KZZD-EW-TZ-08, GJHZ1214), and Key Directional Program of the Chinese Academy of Sciences (KZCX2-YW-338-2).

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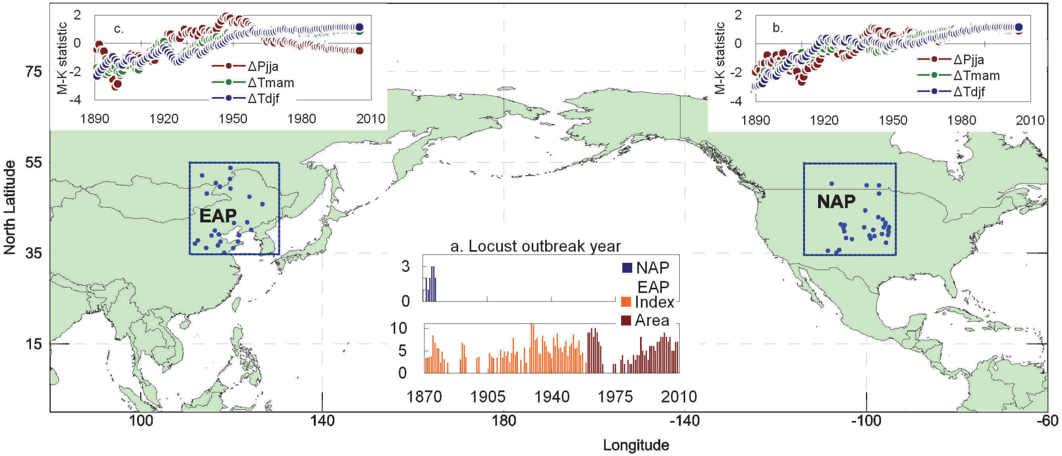

Fig. 1. Maps of study areas with meteorology station locations, information of locust outbreaks **(a)** and climate changes in NAP **(b)** and EAP **(c)**. All codes of climate variables are the same as text.

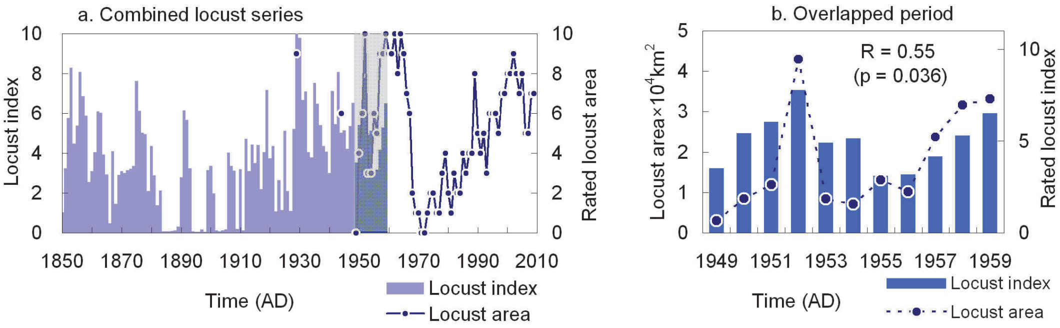

Fig. 2. Joined series of locust outbreak data in EAP, including the severity index based on history literature (blue bar) and the area index based on observed locust stricken area (blue dot-line) **(a)**. Grey box in a enlarged the overlapped period of during 1949–1958 AD, showing that two data series was significantly correlated **(b)**.

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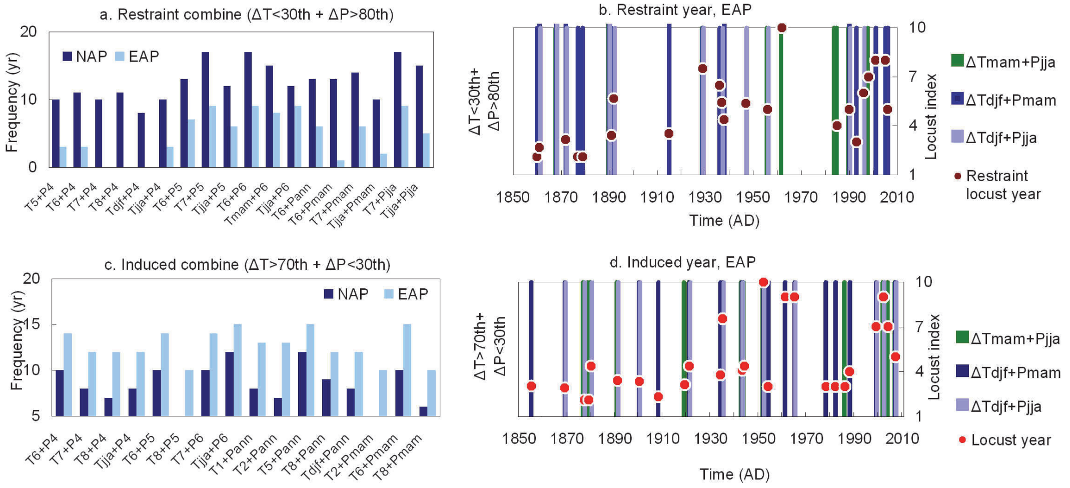

Fig. 3. Frequency comparisons of climatic extreme combinations between NAP and EAP **(a, c)** and validation with EAP locust outbreak years **(b, d)**, including restraint model with $\Delta T > 70$th and $\Delta P < 30$th percentiles **(a)**, induced model with $\Delta T < 30$th and $\Delta P > 80$th percentiles **(c)**, year comparisons of locust outbreak with warm-dry extremes ($\Delta T > 70$th and $\Delta P > 30$th) **(b)** and cold-wet extremes ($\Delta T < 30$th and $\Delta P > 80$th) **(d)**. All codes of climate variables are the same as text.

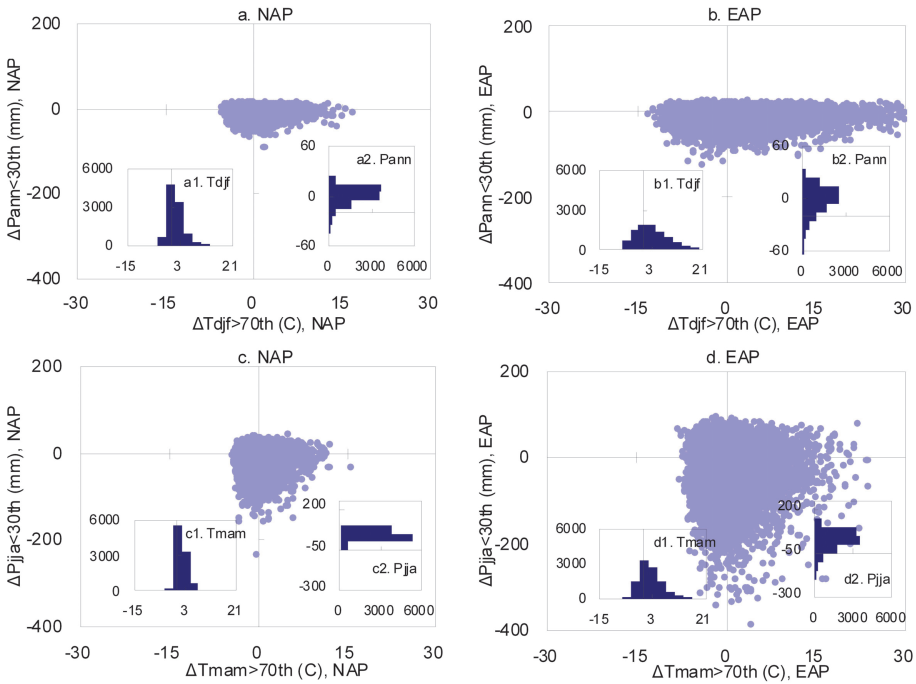

Fig. 4. 2-D-scatter diagrams of Gumbel-distribution climate extremes in NAP and EAP. Combinations $\Delta T > 70$th and $\Delta P < 30$th percentiles **(a, b)** and $\Delta T < 30$th and $\Delta P > 70$th percentiles **(c, d)** for NAP **(a, c)** and EAP **(b, d)** respectively. Frequency diagrams at 8 panels of a1, a2, b1, b2, c1, c2, d1 and d2 were plotted for 10 000 samples of ΔT (along x-axis, unit in Celsius degree) and ΔP (along y-axis, unit in mm). All codes of climate variables are the same as text.

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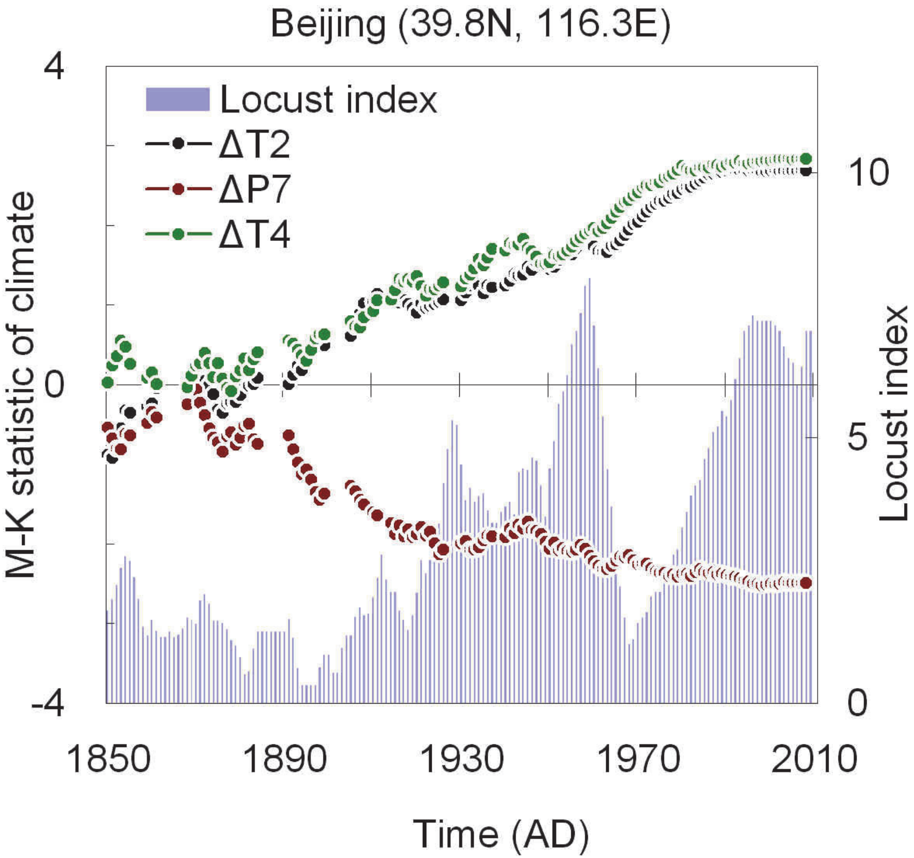

Fig. 5. Comparisons of locust outbreaks with trends of climate changes in Beijing by using M-K trend test ($p < 0.05$). P7, T2 and T4 represent July precipitation, February and April temperatures respectively.