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Climatic and lake environmental changes in the Serling Co region of Tibet over a variety of timescales

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The Serling Co region is located at the transitional zone of the interaction between the Indian monsoon and the westerlies over the Tibetan Plateau. The Serling Co lake covers a water area of 2,389 km^2 (June 2017) in a 45,530 km^2 drainage basin. Under the dramatic hydro-meteorological changes on the Tibetan Plateau in recent decades, and complex hydrological compositions of rivers and lakes in the basin, the lake area expanded by 43%, from 1,667 km^2 in 1976, to 2,389 km^2 in 2017 [1]. In 2014 it surpassed Nam Co as the largest lake on the Tibetan Plateau [2], and exerts significant effect on regional environmental conditions.

The Second Tibet Plateau Expedition Program, launched in 2017, targeted the Serling Co region as one of the key sites for a comprehensive survey focusing on recent changes in lakes, rivers, glaciers and atmospheric conditions in the region. This program collected a large number of samples for a range of scientific analyses (Fig. S1 online). Results from this work showed that regional environmental conditions have changed profoundly in the 40 years since the first Tibet Plateau Expedition. The data collected provide a model for research involving ecosystem evolution under different climate change scenarios in the future.

From 1979 to 2017, average annual temperature at the Serling Co increased significantly at the rate of 0.049 °C a^{-1}, with autumn temperature increasing 110% faster than in spring. The average annual precipitation increased at the rate of 4.65 mm a^{-1}, with main increase occurring after the mid-1990s (Fig. S2 online).

The lake survey showed that the water area and storage of the Serling Co lake were 2,389.47 km^2 and 558.38 $\times 10^8$ m^3 in 2017, with 710.51 km^2 and 249.01 $\times 10^8$ m^3 increases than that in 1972, respectively. The average annual increase was 15.64 $km^2\ a^{-1}$ and 4.25 $\times 10^8\ m^3\ a^{-1}$, respectively, but they were slower in 1972–2000 with 9.124 $km^2\ a^{-1}$ and 3.68 $\times 10^8\ m^3\ a^{-1}$, and showed rapid increase in 2000–2005 with 60.69 $km^2\ a^{-1}$ and 15.76 $\times 10^8\ m^3\ a^{-1}$, respectively. However, in 2005–2017 the rate of increase slowed, with only 12.63 $km^2\ a^{-1}$ and 5.53 $\times 10^8\ m^3\ a^{-1}$, respectively (Fig. S3 online) [1].

The lake recharge analyses showed that annual precipitation, non-glacial runoff and glacial runoff are 6.0 $\times 10^8$, 20.5 $\times 10^8$ and 2.0 $\times 10^8\ m^3$, which occupied 21.1%, 71.8% and 7.1% of the total recharges, respectively. Comparing recharge to the annual average lake evaporation of 20.4 $\times 10^8\ m^3$ yields, an average annual lake water volume increase of 8.2 $\times 10^8\ m^3$, driving the lake water level increase of about 14 m within past 30 years [3]. The dominant factor driving the Serling Co lake expansion is the increase of non-glacial runoff caused by precipitation, with the weakening of lake evaporation a secondary factor.

Using survey data from 14 lakes in the Serling Co region, an inversion model between transparency and MODIS data was constructed, and showed that the lake transparency has been decreasing since 2000 [4]. The annual variation of lake transparency shows a negative correlation with precipitation in the basin. A survey of the salinity variation of 12 lakes in the Serling Co region showed that the salinity decline may be closely related to the lake expansion in recent decades.

The hydrobiological investigation in lakes of the Serling Co region showed Simpson diversity of phytoplankton decreased with the salinity increase, and increased with the nutrient concentration increase. The salt tolerance of diatoms and their adaptation to low temperature give them a competitive advantage and wide distribution in the Tibetan Plateau lakes [5]. Zooplankton showed low diversity in these lakes with only a small number of widespread species, including paleo-north region species and plateau endemic species. Multiple regression analysis showed that salinity is the main factor limiting the diversity of zooplankton species among lakes. Lake area, lake numbers, altitude and temperature had no significant influence. It is worth noting that the fish predation pressure on zooplankton did not increase with salinity. In lakes without predator distribution, macrozooplankton such as Artemia or Daphnia are dominant, outcompeting other species. In lakes with predator distribution, the selective feeding of predators on large zooplankton can effectively reduce the competitive advantage of

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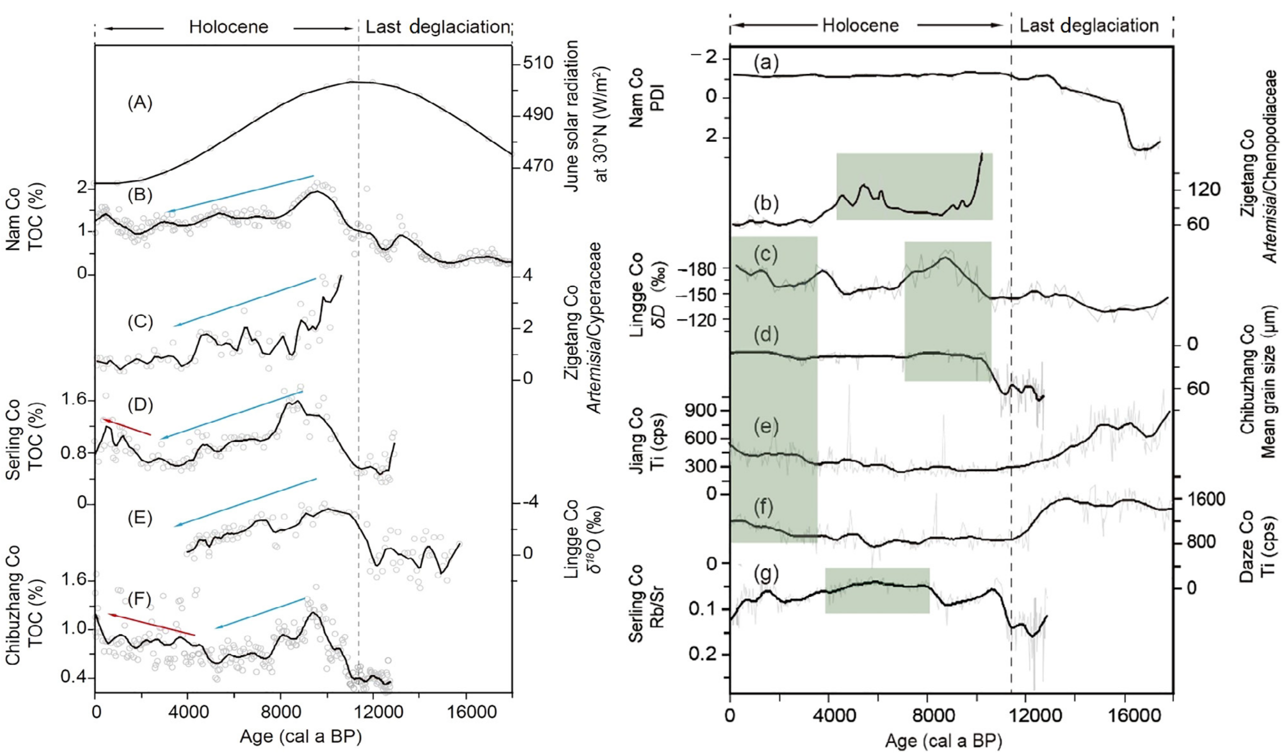

Fig. 1. The environmental changes since last deglaciation period reflected by lakes cores of Lingge Co, Serling Co and Chibuzhang Co together with other literatures. The left part shows variations in temperature, with blue arrows showing the cooling trend and red arrows indicating the warming trend. (A) Solar radiation changes at 30 °N [9]. (B) TOC record from Nam Co [10]. (C) Pollen ratio of *Artemisia*/Cyperaceae in pollen assemblages from Lake Zigetang [11]. (D) TOC record from Serling Co [8]. (E) δ^{18}O record of *Leucocythere mirabilis* shells from Lingge Co [12]. (F) TOC record from Chibuzhang Co. The right part shows the variations in moisture (or precipitation) and green shadows indicate relatively humid periods. (a) Pollen discrimination index (PDI) record from Nam Co [10]. (b) Pollen ratio of *Artemisia*/Chenopodiaceae in pollen assemblages from Lake Zigetang [11]. (c) Weighted average δD values for C_{26}, C_{28} and C_{30} *n*-alkanoic acids from Lingge Co [13]. (d) Mean grain size record of Chibuzhang Co. (e) Ti record from Jiang Co [14]. (f) Ti record from Daze Co [14]. (g) Rb/Sr record from Serling Co [8].

macrozooplankton, thus maintaining higher overall zooplankton diversity [6].

Higher plants identified during the survey include 36 families, 143 genera, 360 species, and 42 varieties or subspecies. Findings include two endemic genera in China, such as *Pomatosace filicula* and *Przewalskia tangutica*, and several endemic species in Tibet such as *Physochlaina praealta*. The survey of wild animals together with three kinds of detection functions (semi-normal, risk rate and uniform detection functions) showed that, the density of Tibetan wild donkey, Tibetan gazelle and Tibetan antelope are 0.511 per square kilometer (standard error is 0.054), 0.290 per square kilometer (standard error is 0.016) and 0.467 per square kilometer (standard error is 0.157), respectively.

The land cover types of the Serling Co watershed include forest, grassland, water, built-up land, and other non-utilized land. Grassland is the most important cover type, accounting for 83.82% of the total watershed area, while water area is 9.44%. Land cover type is relatively stable, showing only 0.14% change during 1990–2015. The lake area increased by 48.51 km^2, mainly inundating grassland and saline-alkali land. Animal husbandry is the main form of land use in this area.

The environmental changes since the last deglaciation period were preliminarily analyzed by using the lacustrine sediment core samples from Lingge Co [7], Serling Co [8] and Chibuzhang Co (Fig. 1). Before 11,500 calendar years before present (a BP), average temperatures were colder as indicated by lower total organic carbon (TOC) in Serling Co and Chibuzhang Co, and highest ostracoda shell δ^{18}O in Lingge Co; and drier as indicated by highest Rb/Sr in Serling Co and the maximum mean grain-size in Chibuzhang Co. The high value of δD of plant wax in Lingge Co indicates that the Indian monsoon was weak and had negligible effects on the lake region in this period. After 11,500 a BP, both the increase of TOC in Serling Co and Chibuzhang Co and decrease of ostracod shell δ^{18}O in Lingge Co indicated rapid warming in the region, which was also supported by higher Artemisia/Cyperaceae values in Zegetang Co during 10,000–8,000 a BP [12]. However, a cooling trend since the middle Holocene occurred in Serling Co and Chibuzhan Co areas until warming again in the late Holocene. Precipitation or humidity variation showed significant spatial differences in the Holocene in this region. The mean grain size from Chibuzhang Co and δD of plant wax from Linge Co suggest relatively wet conditions in early and late Holocene, with drier conditions in the middle Holocene. Artemisia/Chenopodiaceae data from Zegetang Co suggest wet conditions in early and middle Holocene, and drier in late Holocene. At Serling Co, the Rb/Sr values indicated wet conditions in middle Holocene, and drier in early and late Holocene. According to the analysis of regional temperature and solar radiation, it is suggested that solar radiation was probably the dominant factor driving temperature variation across the region, with the possible additional effects of different sources of lake recharge for the three lakes sampled.

Conflict of interest

The authors declare that they have no conflict of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scib.2019.02.016.

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