Journal Pre-proofs

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PII: S2095-9273(20)30391-1
DOI: https://doi.org/10.1016/j.scib.2020.06.012
Reference: SCIB 1109

To appear in: *Science Bulletin*

Received Date: 31 January 2020
Revised Date: 1 June 2020
Accepted Date: 3 June 2020

Please cite this article as: Y. Dai, D. Chen, T. Yao, L. Wang, Large lakes over the tibetan plateau may boost snow downwind: implications for snow disaster, *Science Bulletin* (2020), doi: https://doi.org/10.1016/j.scib.2020.06.012

Short Communication

Large lakes over the Tibetan Plateau may boost snow downwind: implications for snow disaster

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Received 2020-01-31，revised 2020-06-01，accepted 2020-06-03

There are more than 1200 lakes (>1 km^2) on the Tibetan Plateau (TP), covering a total area about 47,000 km^2. The role of lakes on regional climate is significant because they can regulate regional precipitation distribution[1,2], particularly snow cover[3], through lake-atmosphere interaction. Lakes are also known to act as heat sources during winter due to their different heat capacity with the surrounding land[3]. When cold air passes over relatively warm surface of an unfrozen lake, atmospheric instability and vertical motion of air increase, and water vapor from the lake surface is taken up to the air and may be released as lake effect snow (LES) over and/or downwind of the lake[1,3]. Thus, snow cover can be initiated or significantly enhanced by this effect.

Previously study on the Nam Co, one of the biggest lakes (surface area reaches about 2200 km^2) on the TP, found an evident lake effect that increased precipitation (or snowfall) to the east of Nam Co compared to that in the west[4]. It is important to understand LES on the whole TP because snow cover plays an essential role in the regional hydrological cycle and can affect local thermal conditions[5]. In dry season (October - March), snowmelt can increase soil moisture and promote the growth of pasture.

The majority of the lakes on the TP are located in the inner TP, and most of them appear in large and distinct groups. Previous studies[6,7] divided them into the north and south lake areas. The lakes in the northern part on the TP are generally small, about 88% of them have an area between 1 and 200 km^2. Lakes in the north are generally frozen before November[7], and thus the LES there is relatively insignificant. Most of the large lakes on the TP are located in the south of Qiangtang lake region. Nine of these lakes have an area larger than 400 km^2. They are located at latitudes between 31° and 32°N, including two lakes larger than 2000 km^2. Lakes in the south generally freeze in December[7]. Here we focus on the lake effect of the large lakes along the 31°−32°N belt in the south TP (**Figure 1**).

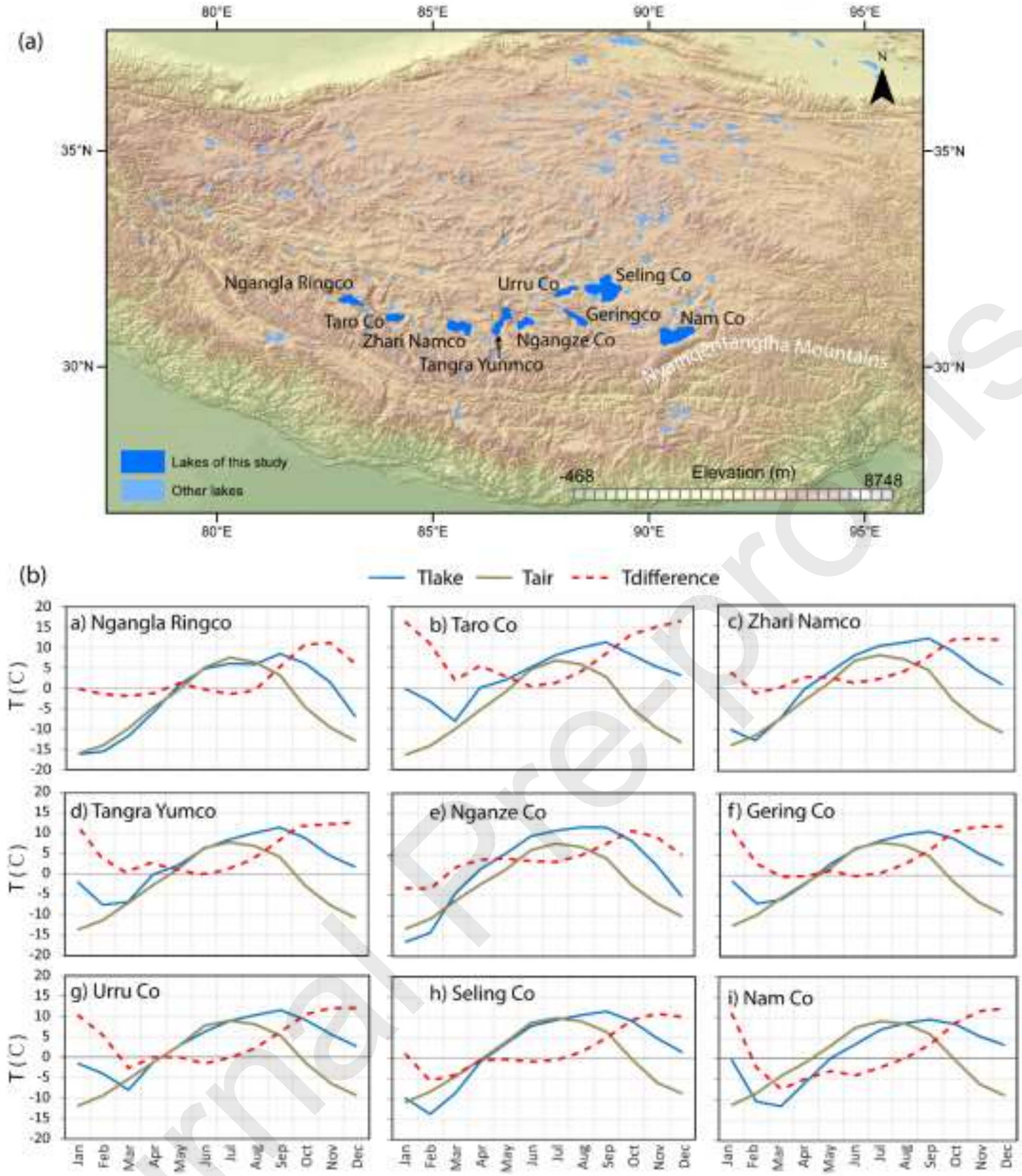

Figure 1. The study area and lake-2m air temperature difference. (a) Large lakes distribution along the 31−32°N belt in the southern part of the TP; (b) monthly lake surface and air temperature averaged over 2002-2017 for group lakes of the southern TP. T_{lake} indicates the temperature of lake surface, and T_{air} indicates the 2-m air temperature surrounding the lake. The monthly lake surface temperature data are calculated by the MODIS Land Surface Temperature Data Product (MOD11A2), while the monthly 2-m air temperature data are derived from ERA-Interim monthly reanalysis datasets.

The lake-air temperature difference is the most important environment factor that contributes to LES[3]. The group lakes region reached its highest average 2-m air temperature in July, and then fell below zero since October (**Figure 1**). The lake surface temperature reached its maximum in September, gradually fell below 0℃ since December and completely frozen during December and January. In general, under the unfrozen condition, the lake-air temperature difference of group lakes was largest from October to December (>10℃), and reached its maximum in November (about 12℃). Because of the large heat capacity of water, the peak value of lake surface temperature lags behind the peak value of air temperature over land. Meanwhile, the beginning of the temperature below 0℃ in lakes is later than that in the air over land.

Both wind direction and intensity play roles in the LES. Sousounis[8] found that Based on sensitivity testing with a numerical model, the largest snow in the downwind area of lakes happens under a moderate wind speed (4–6 m s^{-1}) rather than a weak wind speed (0–4 m s^{-1}) or strong wind speed (6–16 m s^{-1}) generates the largest snow in the downwind area of lakes. The wind direction has a greater impact on LES than wind speed[9] because it determines the spatial distribution of snow cover. According to wind diagram for surface wind (10 m) of each lake in the study region during the October and December between 2002 and 2017 (**Figure S1 online**), the upwind region is mainly in the west, southwest and northwest, and downwind region in the east, northeast and southeast. The average wind speed is about 4-6 m s^{-1}, providing favorable conditions for LES.

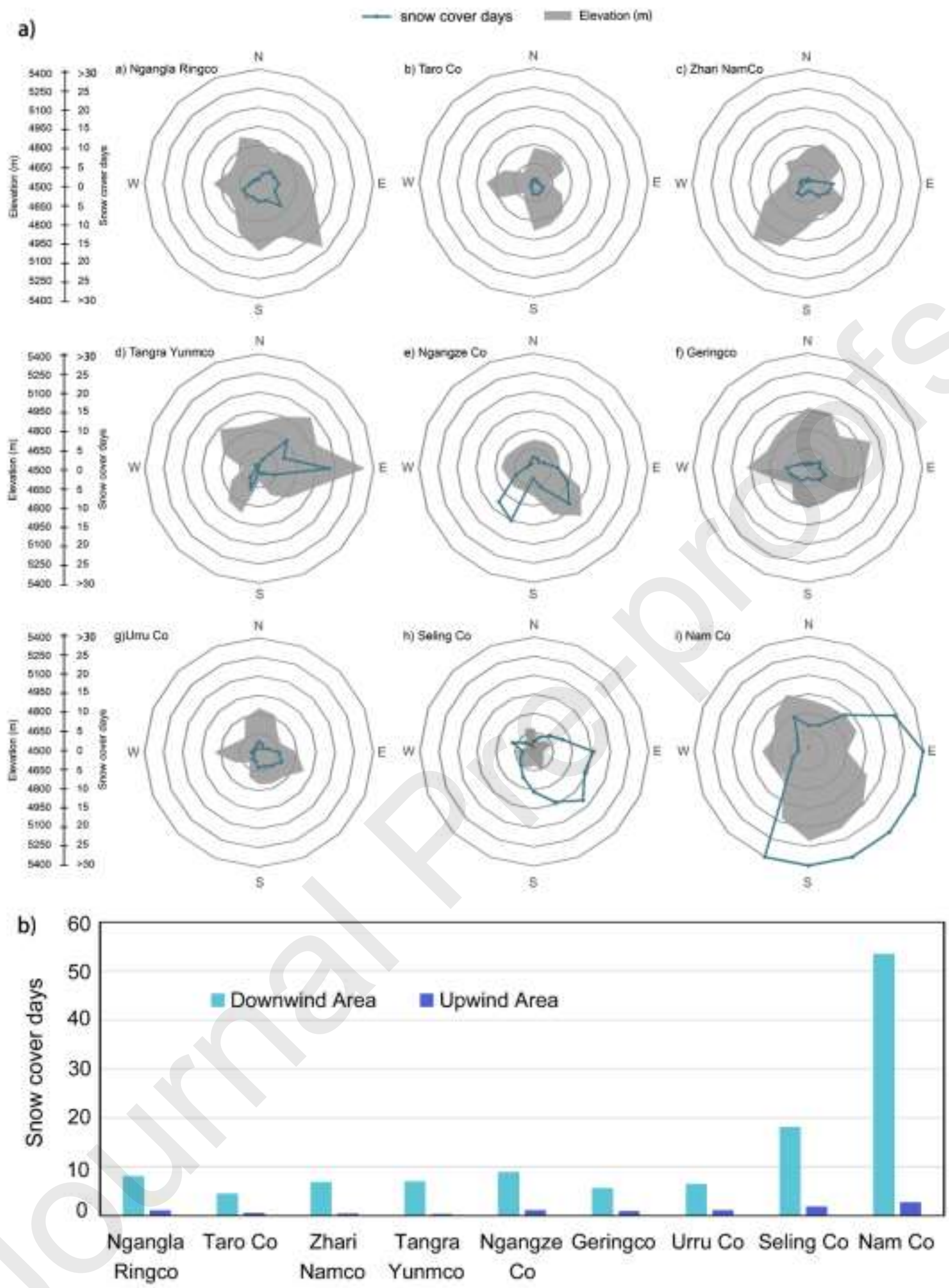

Figure 2. Spatial distribution of snow cover days. (a) Spatial distribution of multi-year average (2002-2017) snow cover days during October and December and corresponding DEM distribution. Taking the lake as center, 10 km buffer zone is selected to calculate the average topography (Gray shadow) and the snow cover days (blue line) in 16 different directions. (b) Multi-year average (2002-2017) snow cover days of upwind and downwind during October and December. The daily fractional

snow cover data set is derived from the MODIS normalized snow index data with a spatial resolution of 500 m.

According to the multi-year average (2002-2017) snow distribution (**Figure 2**), the number of snow cover days in downwind area was much greater than that in upwind area. We identified that the LES of these large lakes mainly occurred from October to December, in the downwind areas of the lakes, i.e., to the east, southeast and northeast of the lakes, even though the terrain changes around those lakes.

The most significant LES event occurred around the two largest lakes on the TP, Nam Co (2015 km^2) and Seling Co (2385 km^2), when they are in the downwind area of the group lakes. Specifically, the number of mean annual snow cover days is about 50 d in the downwind area of Nam Co and 3 d in the upwind area, from October to December. The number of snow cover days is about 18 d in the downwind area in Seling Co and 2 d in the upwind area from October to December. The significant LES events around the two lakes related to their large lake area. Besides, the east-west axis of the lake shape and the existence of Nyainqentanglha Mountain also play a role. On one hand, the east-west axis of Nam Co and Seling Co are also the largest in the lake group, about 75-80 km. When the westerly dominated, the east-west axis of the lake shape fully guarantees the fetch distance of cold air on the lake surface. On the other hand, with the existence of Nyainqentanglha Mountain, the airflow lifted along the upwind slope, which benefited the precipitation in the downwind region of Nam Co and thus strengthened the lake effect.

LES runs the gamut from flurries to heavy snowstorms. LES storm is a prominent meteorological phenomenon during the winter in the Great Lakes Basin[10]. The snow cover days of group lakes of the southern TP varied greatly during 2002-2017 (**Figure S2 online**), especially in the downwind of Nam Co and Seling Co, with a standard deviation larger than 10 d from October to December. The average number of snow cover days fluctuated greatly in the downwind areas of these two lakes, and the instability of snow cover days increased. LES plays an important role on the variability of the snow cover days over these lakes for the following reasons. Firstly, there is a big difference in the snow cover days in the lake downwind areas between the years with and without LES. Secondly, the intensity and the occurrence date of LES vary at different years, and may have resulted in very different speed of snow melting, leading to large inter annual variability of snow cover days caused by LES.

According to the observed data from 2005 to 2018 at Nam Co Station, which is located approximately 2 km to the southeast of Nam Co Lake, there were 16 events of extreme precipitation (greater than 10 mm per day) in these 14 years from October to December. Although the extreme precipitation events account for only 1% of all daily precipitation events during October and December[4], they showed an upward trend from 2005 to 2018 at the Nam Co station (**Figure S3 online**) and cause disasters. The most serious one was between October 4 and 8, 2018. On October 3, 2018, a gust of cold air passed over the group lakes area, causing the daily minimum temperature of the region to drop by about 4.5°C within 24 h. At the same time, the lake-air temperature difference of the group lakes was about 9°C according to the MOD11A2 and ERA5 daily reanalysis datasets. During snowfall, the airflow of the group lakes moved upward, especially in the lower troposphere (**Figure S4 online**). The specific humidity over the lake-group region also decreased rapidly with the occurrence of snowfall events (**Figure S5 online**). The influence area of LES was about 8000 km^2 (**Figure S6 online**). During the snow period, the snow depth to the east of Nam Co was more than 50 cm while it was only 5 cm in the west of Nam Co. This was the largest snowfall event in October since recording began at the Nam Co station in 2005. Reported by the Nam Co station, the snowfall damaged a large number of houses and all the people in the region had to evacuate after the snow disaster. At the same time, the LES in the Seling Co area mainly distributed to the east of the lake.

The LES on October in 2018 was generally reproduced with WRF simulation. On October 4, 2018, the LES appeared in the east shoreline of Nam Co and neighboring lakes (**Figure S7 online**), with the strongest in the east of Nam Co and northeast of Ngangla Ringco. The LES of Nam Co lasted until October 5, 2018. On October 6, 2018, large-scale snowfall was simulated in the group lakes (**Figure S8 online**), with a heavy LES in the northeast of Ngangla Ringco. On October 7, 2008, LES appeared in the southeast shoreline of the lakes. On October 8, 2018, the LES of east group lakes had increased. The LES intensity of Seling Co over the east and south shoreline was the largest on October 8, 2018. This series of complex snowfall resulted in snow disaster to the east of Nam Co.

According to the annals of Dangxiong County of Tibet in 2017, the snow disaster happened in April 1966, November 1994, and October - November 1997. According to the available remote sensing images (**Figs. S9 and S10 online**) and simulation data (**Figure S11 online**), in October and November 1994, the snow cover area of the lake group was very small, but there was a concentrated snow cover in the eastern part of Nam Co in November. The snow of October - November 1997 had wide coverage (**Figure S11c online**). In October 2018, the distribution of snow disaster was similar with the previous snow disaster of 1994. The heavy snowfall events over the downwind of the lake were mainly due to the lake effect, which induced and strengthened the snowfall. Based on the model simulations, events and the disaster area were concentrated within 50 km of the downwind area of the lakes (**Figure S11b, f online**). Regarding the snow disaster of 1997, the numerical simulations indicate that the lake effect also plays a significant role in enhancing the snowfall in the downwind area (**Figure S11d online**; about 70% contribution to total snowfall). In all the three snow disasters, LES contributed to more than 50% of snowfall in downwind area. Since the occurrence of the snow disaster in October 2018, we have set up an observational network for the group lakes. The physical mechanism of the LES on TP will be explored further in combination with the field measurements in the next study.

The lake effect of the large lakes such as Nam Co on the TP has caused the occurrence of or enhanced the intensity of snow disaster event. As such, the lakes play a significant role in causing regional snow disaster on the TP. The blizzard caused by the lake effect is a wake-up call to strengthen efforts to prevention and mitigation of natural disasters in the region. Against the background of global warming, the TP is experiencing an amplified warming and a humidification. It is thus imperative to strengthen the research in lake effect to improve our knowledge and capabilities in disaster prevention and mitigation.

Conflict of interest

The authors declare that they have no conflict of interest.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (41801049, 91747201), the Strategic Priority Research Program of Chinese Academy of Sciences (XDA20060401), the Swedish Research Council (VR 2014-5320), and the Swedish National Space Agency (SNSA: 188/18). We acknowledge the valuable discussion with Dr. Xiangyu Li (Institute of Atmospheric Physics, Chinese Academy of Sciences) and Dr. Changgui Lin (SMHI and University of Gothenburg). Also sincere thanks to Zhi Liu (Northwestern University) for his proofreading of this paper.

Author contributions

Yufeng Dai contributed to the drafting of this manuscript and the development and implementation of methodology. Deliang Chen and Tandong Yao contributed to overall framing of the study and revised the draft. Lei Wang contributed to interpretation of the results and revised the draft.

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