Variations of Lake Ice Phenology on the Tibetan Plateau from 2001 to 2017 Based on MODIS Data

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Introduction

There are about 1200 lakes (>1 km²) on the Tibetan Plateau (TP), and many studies have shown that lake ice phenology respond well to climatic and environmental changes. In the context of global climate change, lake ice phenology can be used as a good indicator to monitor the actual impact of climate change.

The MODIS daily snow products are used to extract the freeze-up and break-up dates of lake ice on the TP from 2001 to 2017. The lake ice durations are then calculated, and the spatial variabilities and change rates of lake ice phenology are analyzed. Using reanalysis data and available satellite dataset, the effects of air temperature, lake surface water temperature, and wind speed on lake ice phenology are analyzed. In addition, possible influence of lake locations and physico-chemical conditions on lake ice phenology are also investigated.

Data & Methods

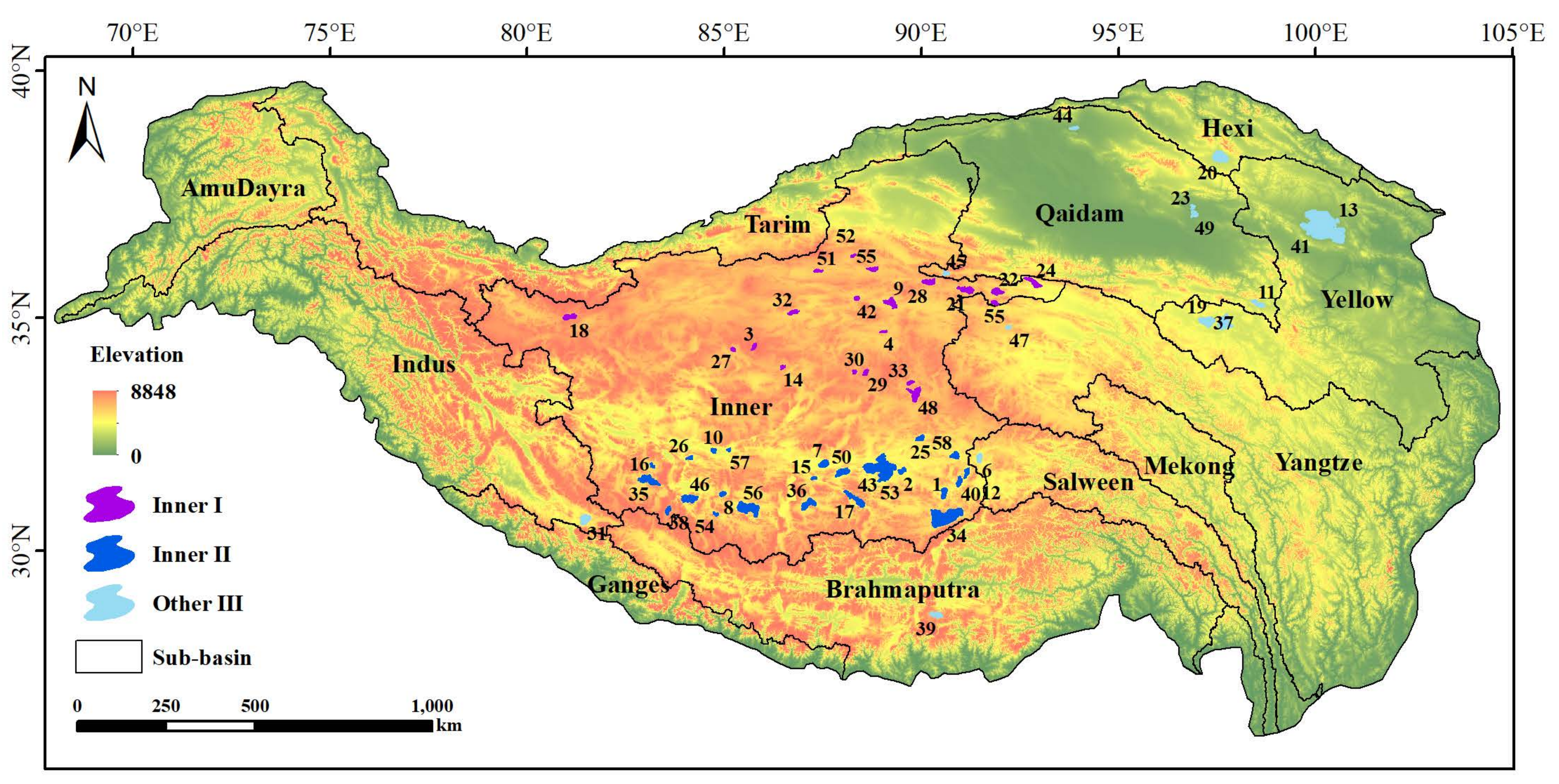

Fig. 1 Locations of the TP and its sub-basins. 58 study lakes are grouped into three sub-areas labeled Inner I, Inner II, and Other III.

Cloud removal process:

- $S_{(A,\, output)}$ = water if $S_{(A,\, Aqua)}$ = water or $S_{(A,\, Terra)}$ = water
- $S_{(A,\, output)}$ = cloud if $S_{(A,\, Aqua)}$ = cloud and $S_{(A,\, Terra)}$ = cloud
- $S_{(A,\, t)}$ = water if $S_{(A,\, t-1)} = S_{(A,\, t+1)}$ = water
- $S_{(A,\, t-1)}$, $S_{(A,\, t)}$ = water if $S_{(A,\, t-2)} = S_{(A,\, t+1)}$ = water
- $S_{(A,\, t)}$, $S_{(A,\, t+1)}$ = water if $S_{(A,\, t-1)} = S_{(A,\, t+2)}$ = water

Freeze-thaw dates extraction:

- $Th_h = 95\% \cdot M_h + 5\% \cdot M_l$
- $Th_l = 5\% \cdot M_h + 95\% \cdot M_l$

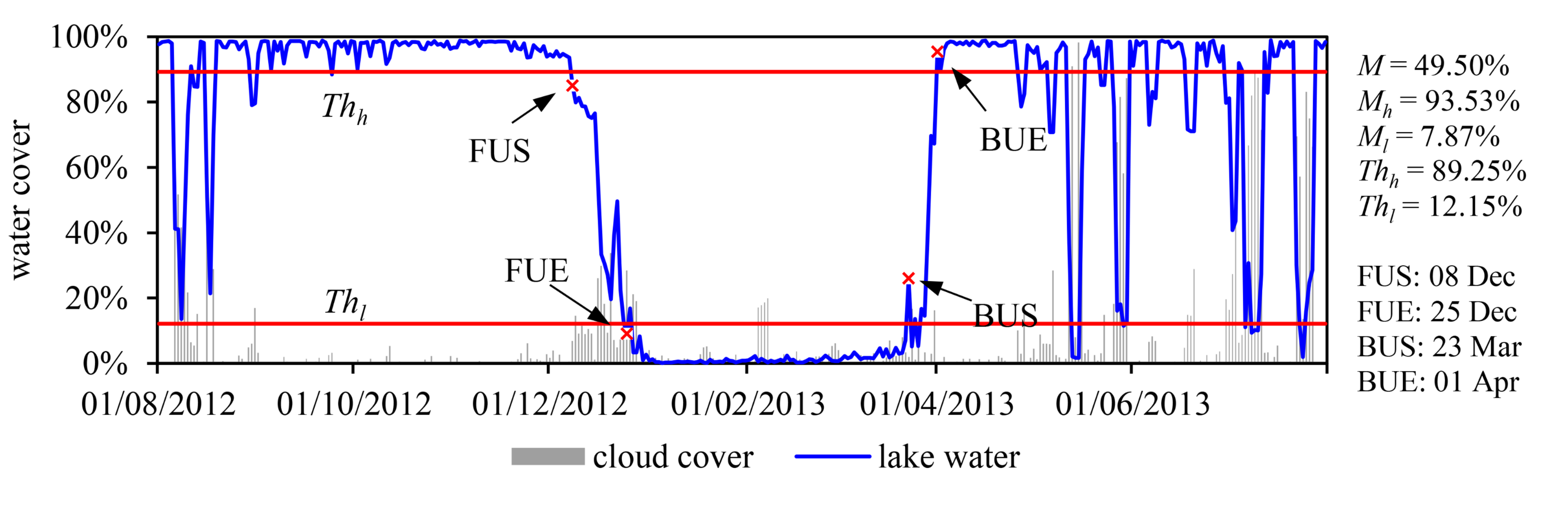

Fig. 2 The extraction of the freeze-thaw dates in Qinghai Lake during 2013. Two red lines represent the two thresholds for extracting freeze-thaw dates, and four red stars, from left to right, represent the freeze-up start (FUS), freeze-up end (FUE), break-up start (BUS), and break-up end (BUE) dates.

Results & Analysis

Table 1 Comparison of cloud cover for 58 lakes during 2013, with and without cloud removal.

	Mean	Maximum	Minimum
Original Terra	44.97%	63.98% (Taiyang Lake)	30.07% (Zhaxi Co)
Original Aqua	51.70%	69.43% (Taiyang Lake)	31.47% (Mapam Yumco)
Combined T&A	31.02%	50.94% (Taiyang Lake)	18.58% (Lagkor Co)
Cloud removal	16.54%	35.49% (Taiyang Lake)	4.52% (Zhari Namco)

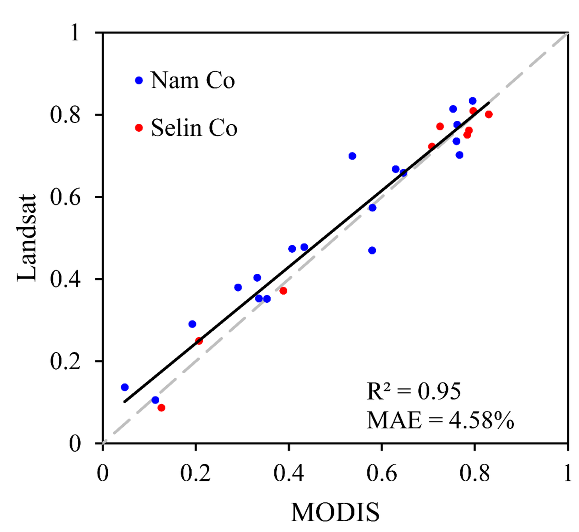

Fig. 3 Comparison of lake water cover proportions derived from the MODIS cloud-removed data and Landsat data.

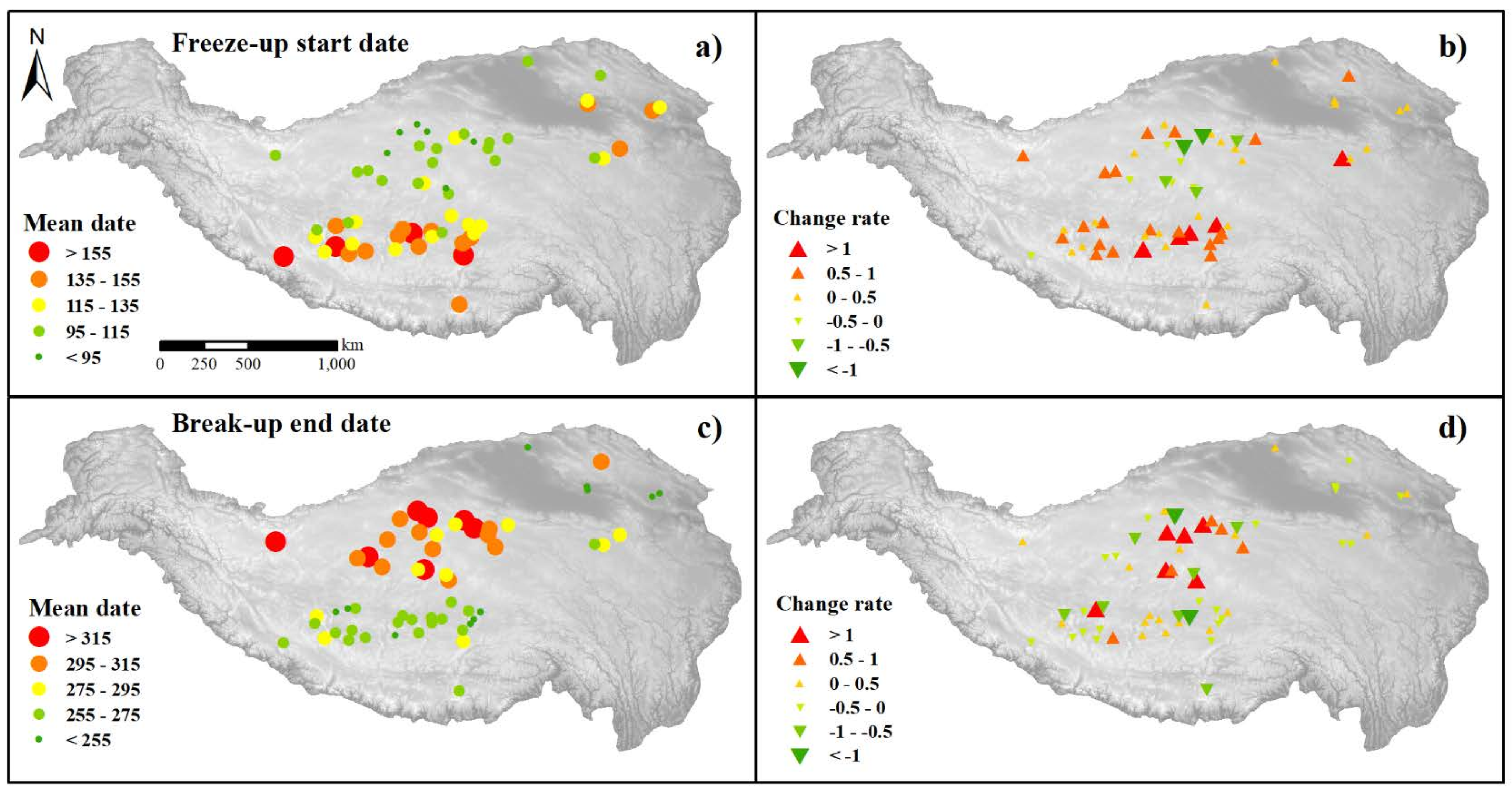

Fig. 4 Mean and change rate of freeze-up start and break-up end dates of the 58 lakes from 2001 to 2017.

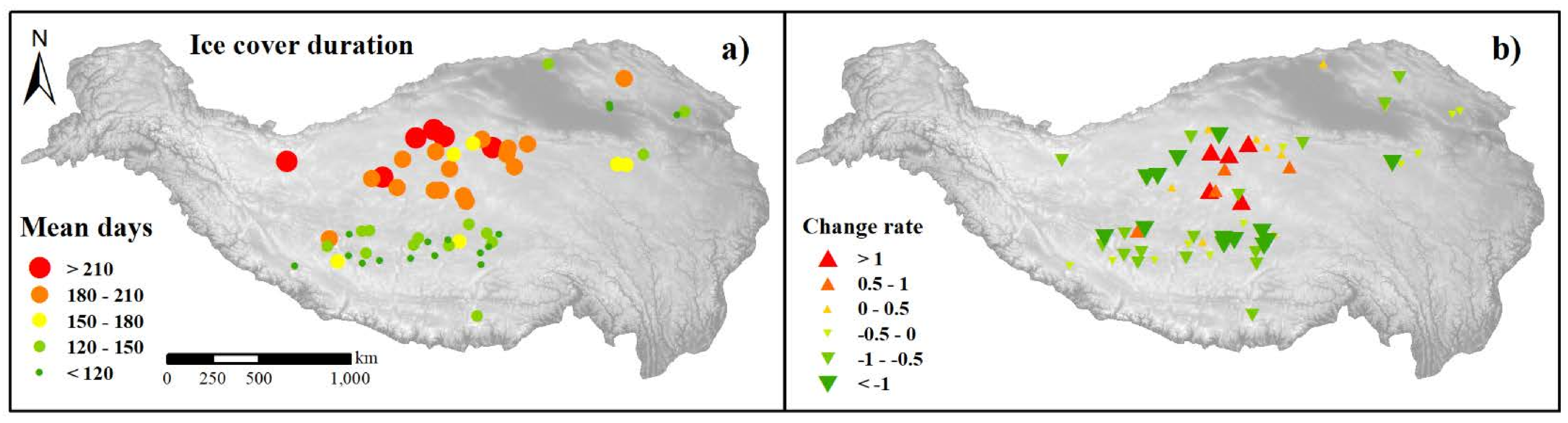

Fig. 5 Mean and change rate of ice cover duration for the 58 lakes from 2001 to 2017

Table 2 The number and percentage of lakes, their mean date/days and change rates within different sub-areas.

		Inner I	Inner II	All lakes
FUS	Mean (all)	20 (34.48%), 10 Nov	24 (41.38%), 13 Dec	58 (100%), 30 Nov
	Delaying	10 (50.00%), 0.57	24 (100.00%), 0.64	47 (81.03%), 0.55
	Advancing	10 (50.00%), -0.49	0	11 (18.97%), -0.44
BUE	Mean (all)	3 Jun	20 Apr	6 May
	Delaying	12 (60.00%), 1.21	11 (45.83%), 0.32	29 (50.00%), 0.69
	Advancing	8 (40.00%), -0.51	13 (54.17%), -0.44	29 (50.00%), -0.39
ICD	Mean (all)	204.46	128.21	157.78
	Extending	11 (55.00%), 1.62	3 (12.50%), 0.41	18 (31.03%), 1.11
	Shortening	9 (45.00%), -0.92	21 (87.50%), -0.89	40 (68.97%), -0.80

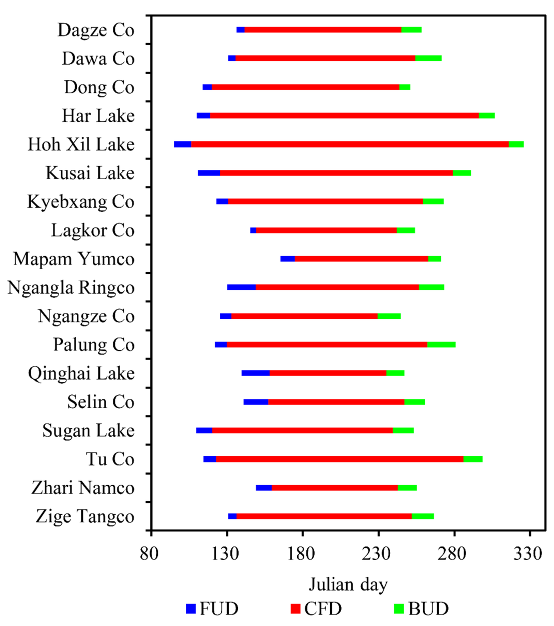

Fig. 6 The freeze-up and break-up processes for 18 lakes.

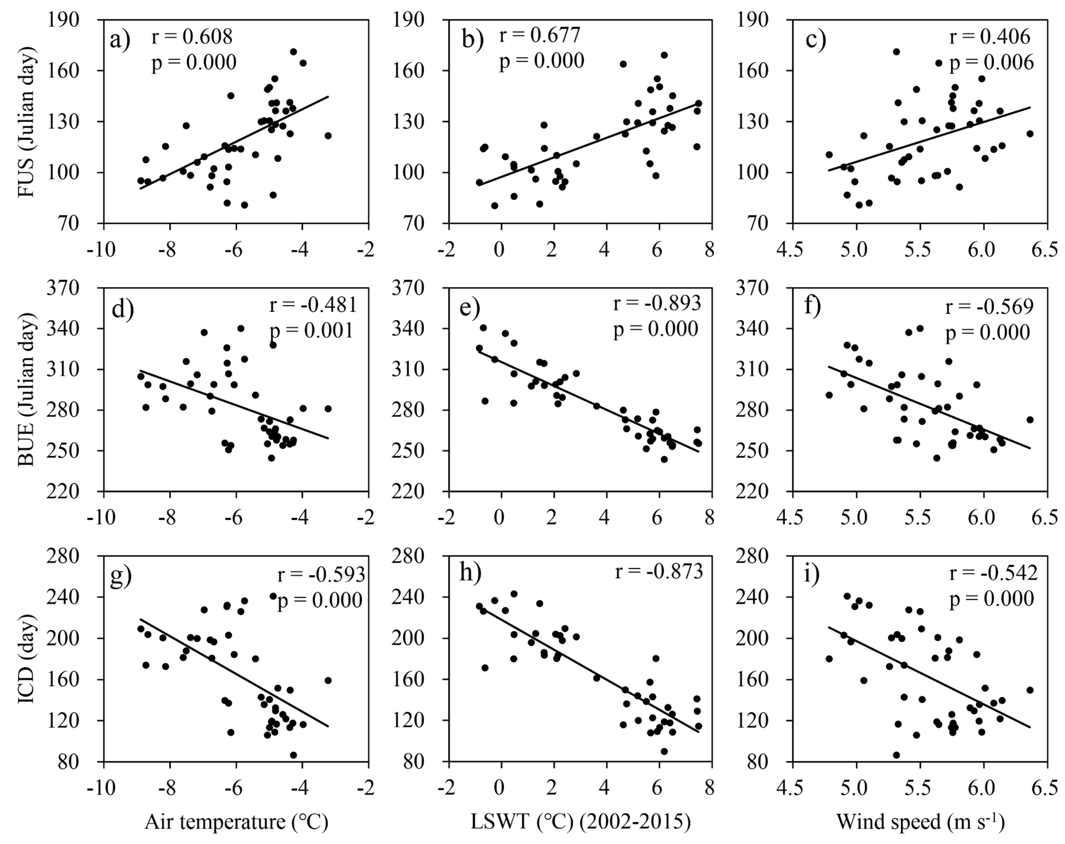

Fig. 7 Correlations between mean air temperature, LSWT, wind speed and mean lake ice phenology parameters in the Inner basin from 2001 to 2017.

Table 3 The number of lakes whose ice phenology has a significant correlation ($p < 0.05$) with climatic factors, and the mean change rates.

	Air temperature (d °C⁻¹)	LSWT (d °C⁻¹)	Wind speed (d m⁻¹ s)
FUS	7, 8.53	9, 2.55	7, 13.89
BUE	10, -11.11	30, -14.56	11, -26.83
ICD	17, -13.75	23, -18.87	16, -29.81

Table 4 Correlations between ice phenology and the physical attributes of the lakes in the Inner I and Inner II.

		Altitude	Area	Mineralization
Inner I	FUS	0.24	0.44	-0.04
	BUE	0.52*	-0.03	-0.28
	ICD	0.28	-0.26	-0.24
Inner II	FUS	-0.03	0.48*	-0.17
	BUE	0.65**	0.18	-0.03
	ICD	0.34	-0.32	0.15

Conclusions

- Approximately two-thirds of the cloud cover from the MODIS daily snow cover products can be removed by combining Terra and Aqua data and by using the pixels within 2 days.
- Lakes on the TP begin to freeze-up in late October, and all the lakes enter the ice cover period in mid-January of the following year. In late March, some lakes begin to break-up, and all the lakes cease to be ice covered in early July.
- Over 17 years, the mean ice cover duration of 58 lakes is 157.78 days, of which the ice cover durations of 18 lakes have extended by a mean rate of 1.11 d yr^{-1}, and those of the other 40 lakes have shortened by a mean rate of 0.80 d yr^{-1}.
- The lakes in the northern Inner-TP have earlier freeze-up dates and later break-up dates (i.e. longer ice cover durations) than do the lakes in the southern Inner-TP.
- The geographical location and climate conditions determine the spatial heterogeneous of the lake ice phenology, especially the break-up dates, while the physico-chemical characteristics mainly affect the freeze-up dates of the lake ice.