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Analysis of ice phenology of lakes on the Tibetan Plateau from MODIS data

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Abstract

Much attention has recently been paid to the impact of climate change at the Tibetan Plateau. This remote and harsh region includes a large system of endorheic (closed basin) lakes. Ice phenology i.e. the timing of freeze-up and break-up and the duration of the ice cover may provide valuable information about climate variations in this region. The ice phenology of 59 large lakes on the Tibetan Plateau was derived from Moderate Resolution Imaging Spectroradiometer (MODIS) 8-day composite data for the period from 2001 to 2010. Duration of the ice cover appears to have a high variability in the studied region due to both climate and local factors. Mean values for the duration of ice cover were calculated for four groups of lakes defined as distinct geographic regions. In each group several lakes showed anomalies in ice cover duration in the studied period. Possible reasons for such anomalous behavior are discussed. Furthermore, many lakes do not freeze up completely during some seasons. This was confirmed by inspection of high resolution optical data. Mild winter seasons, large water volume and/or high salinity are the most likely explanations. Trends in the ice cover duration derived by linear regression for all the studied lakes show a high variation in space. A correlation of ice phenology variables with parameters describing climatic and local conditions showed a high thermal dependency of the ice regime. It appears that the freeze onset and water clean of ice day appear to be more thermally determined than freeze-up and break-up dates in case of the studied lakes.

1 Introduction

Tibetan Plateau (TP) was identified as one of the most sensitive regions of the world to changes in climate (Liu and Chen, 2000). At the same time, because of its unique properties, TP has a strong impact on the global climate system, acting as a large heat source and moisture sink during the summer (Ueno et al., 2001; Hsu and Liu, 2003; Sato and Kimura, 2007). It impacts the monsoon circulation as a barrier to zonal

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and meridional air motion (e.g. Kurzbach et al., 1993; Barry, 2008). Recently many studies have been focused on various aspects of climate change impact on the TP but our knowledge of its mechanisms and regional variations is still limited. An unbiased analysis of the impact of the changing climate on the TP is often hindered by lack of ground measurements. Sparseness of meteorological stations, rough conditions and difficult accessibility call for the use of remote sensing methods. Variations in climate in this area are reflected by several phenomena that are well documented by satellite records such as snow distribution (Shreve et al., 2009; Xu et al., 2009; Kropáček et al., 2010), changes in glacier extent (Ye et al., 2006; Bolch et al., 2010) or fluctuations in lake area (Bianduo et al., 2009) that can be therefore seen as climate indicators.

An important indicator of changes in climate derived from satellite data is lake ice phenology. This has been proved in a number of recent studies on regional (Ruosteenoja, 1986; Barry and Maslanik, 1993; Duguay et al., 2006; Che et al., 2009) and global scales (Walsh et al., 1998; Menguson at al., 2000). Interannual variation in lake ice phenology allows estimates of local climatic variability (Walsh et al., 1998). The lakes on the TP are distributed mainly in the central and western part, while meteorological stations are concentrated in the eastern part of the plateau (Liu and Chen, 2000). Derivation of lake ice phenology of Tibetan lakes could therefore fill a gap in our knowledge about the impact of climate change in this remote region.

1.1 Lake ice phenology

Ice phenology deals with periodic formation and decay of ice cover over water bodies and changes in its timing as a result of seasonal and inter-annual variation in climate. Formation of ice cover affects water bodies in high latitudes and altitudes where the temperature during cold season falls below 0 °C for a sufficiently long time period. Appearance of ice is initiated when the lake surface water temperature falls below 0 °C. The date when detectable ice appears is referred to as the Freeze Onset (FO) in this study. The ice formation begins along the shore of shallow bays. Ice growth, especially during the formation of a new thin ice, can be interrupted by strong wind events. The date of the end of the freeze- up period, when the total ice cover is denoted as Freeze-up Date (FU) in this study. An increase of temperature of the air above and of the water below the ice in spring leads to a thinning of the ice and eventually to the ice break up. Appearance of a detectable ice free water surface, after which no more total freeze up occurs, is called Break-up date (BU) in the following. Further deterioration of the ice leads to an eventual disappearance of ice denoted as Water Clean of Ice (WCI) .

Since there are differences in definition of variables describing the duration of lake ice cover a comparison of ice phenology records for different regions is often biased (Brown and Duguay, 2011). Here we use two variables describing the duration of ice cover: Duration of Ice Cover (DI) which results from subtraction of the WCI and FO and Duration of Complete Ice Cover (DCI), which is defined as the period between BU and FU. Many lakes on the plateau freeze up as late as in January or February. A freeze-up in December or November is counted to ice cover of the following year for sake of simplicity since it belongs to the same ice cycle. The choice of lake ice phenology variables as climate indicator varies among authors. Liston and Hall (1995) suggest that FU and BU together with maximum ice thickness are useful indicators of regional climate change, while Latifovic and Pouliot (2007) use the end of freeze-up and the end of break-up in their analysis of lake ice phenology in Canada instead. However their choice was influenced by the availability of comparable in-situ data.

1.2 Factors influencing the lake ice phenology

Sensitivity of lake phenology to climate variables have been investigated by several authors. It was proved that BU/FU are highly sensitive to changes in air temperature. Using a numerical simulation a delay of as much as 4 weeks in freeze-up and break-up dates has been found by Liston and Hall (1995) for St Mary Lake in Canada in reaction to change in air-temperature for 4 °C. They also report a sensitivity of ice phenology to a decrease in wind speed, which amounts for 2 weeks for Great Slave Lake in Canada. The air temperature has been suggested as the most significant factor that influences the ice phenology for instance by Livingstone (1997) and Kourayev et al. (2007). Analysis of ice phenology of numerous lakes and rivers in the Northern Hemisphere showed that a 1 °C change in mean air temperature corresponds to a change of about 5 days in the duration of the ice cover season (Skinner 1993, Magnuson et al., 2000). However Weyhenmeyer et al. (2004) suggested that the relationship of temperature and break-up date is non-linear, leading to more sensitive reactions of ice break-up date to temperature changes in cold regions. However it is not only climate that determines the ice regime of lakes. There are several factors that affect both the duration of ice cover and the timing of ice phenology events which can be divided into local and climate factors. Apart from temperature climate related factors include wind speed and snow cover, which acts as an insulating layer. The absence of snow cover thus results in thicker ice cover and this leads in turn to later break-up (Kouraev et al., 2007). The local factors that have a relation to the ice regime of lakes are: lake bathymetry, salinity, altitude, shape of the shoreline and lake area. Some facts regarding the importance of particular factors for the lake ice regime can be proved by modeling of the lake ice cover. Ménard et al. (2002) for instance showed that lake depth is a determinant of freeze-up date for Canadian lakes using a one-dimensional thermodynamic lake ice model.

1.3 Effects of lake ice phenology on local or regional climate

While the lake ice phenology is impacted by climate change, the lake ice regime can in turn influence the local or even the regional climate. The freeze-up and break-up processes lead to an abrupt change of the lake surface properties (e.g. albedo), affecting mass and energy exchange between lake water and atmosphere. The lakes basically act as heat sinks in summer and heat sources in winter (Haginoya et al., 2009). The variation in ice phenology affects the amount of on-lake evaporation since the lake ice blocks the water-air interface and the sublimation does not compensate this effect.

A deep lake such as Nam Co can supply a large amount of heat energy to the atmosphere in the post-monsoon period (Haginoya et al., 2009). Air masses passing over a large relatively warmer open water area during winter can lead to heavy snow

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fall on the downwind shore. This so called lake effect is well known in case of the large Lurentinan Great Lakes (Eichenlaub, 1970). For TP the lake effect has been described in the case of Nam Co, which is a large saline lake in the central part of the plateau (Li et al., 2009) and has been analyzed by remote sensing data by Kropáček et al. (2010). This exchange process is obviously interrupted by lake freeze-up when no more warmer open water is available. The relation of the lake freeze-up and lake effect determined snow cover in Nam Co Basin has been compared on time series of optical satellite and passive microwave data by Kropáček et al. (2011a).

1.4 Objectives

So far little attention has been paid to the ice regime of lakes on the TP in comparison with high latitude lakes. Both the of comprehensive analyse of Northern Hemisphere lake ice cover as a response to changing temperature presented by Magnuson et al. (2000) and Dibike et al. (2011) based on ground observations and modeling approaches, respectively, do not include the TP. So far analysis of the ice regime of two large lakes on the TP has been carried out: Qinghai Lake on the NE margin of the TP by Che et al. (2009), using data from a passive microwave satellite instrument, and Nam Co in the Central TP by Ye et al. (2011), using combination of passive microwave and optical satellite data. An overview of lake ice phenology of at least the largest lakes on the TP is to our knowledge still missing.

Ground observations of lake ice phenology on the remote TP with harsh winter conditions are not available. Such cost intensive observations are further complicated in the case of large lakes where the whole lake surface cannot be observed from a shore station (Walker and Davey, 1993). The number of such stations is globally decreasing, for instance in Canada from 140 sites in mid-1970s to less than 20 sites by the end of the 1990s. Obviously the analysis of lake ice phenology on the TP has to rely on satellite observations. This study is focused on the derivation of a time series of lake ice phenology events from MODIS 8-day snow composites for a representative group of lakes on the TP that allows calculation of duration of ice cover period. The relation of ice phenology to (i) local factors and to (ii) climate variables is analyzed in order to assess the potential of ice phenology for the indication of climate oscillation. Additionally a trend in duration of the ice cover in the period from 2001 to 2010 for the studied lakes is derived.

2 Study area

The TP has a mean elevation exceeding 4500 m a.s.l. and it is bordered by the high mountain ranges Karakorum and Himalaya in the South and by Kunlun Shan in the North extending to a length of several hundreds of kilometers.

The climate of the study region is characterized by wet summers and dry and cold winters. Mean temperatures on the TP decreases towards north. The western and southern part of the TP has a mean annual temperature between 0 and 5 °C while it drops to below 0 °C in the northern part of the plateau (Fig. 2). The mean annual temperature in the South in area around Lhasa, that contains only a few lakes exceeds, 5 °C (Xu et al., 2008). Analysis of meteorological records over the last decades reveals that both temperature and precipitation show an increasing trend (Liu and Chen, 2000; Xu et al., 2008). This general climate trend appears to feature some regional differences across the TP. The southeastern part of TP becomes warmer and wetter, the southwestern part follows the same trend but with smaller amplitude, while the northeastern part of the TP turns warmer and drier (Niu et al., 2004).

There are an enormous number of lakes on the TP differing in size, salinity, altitude and shape. Putting the limit of the minimum area to 0.1 km^2 their number reaches almost 6880, covering in total an area of around 43 000 km^2, out of which 1260 lakes exceed 1 km^2 (Jiang et al., 2008). This makes the TP to one of the largest lake systems on the Earth unique in the high elevation conditions. There are 7 lakes larger than 500 km^2 distributed mainly in the SW part of the plateau out of which 4 exceed 1000 km^2. So far there is little known about the bathymetry of even the largest lakes (Wang et al., 2010).

Most of the lakes on the TP are brackish or saline. An overview of salinity in three classes is presented by the "Map of the Lakes and Glaciers on the Tibetan Plateau" (Yao, 2007), while zoning of Tibetan lakes according to their hydrochemical type is described in Zheng and Liu (2009). Additionally several figures on salinity of the Tibetan lakes are dispersed in literature. Nevertheless a comprehensive data set describing the salinity of lakes on the TP is not available. Salinity in the context of limnology represents the total sum of ions dissolved in water. Most of the lakes on the TP represent a termini of inland drainage basins and are therefore salty. Only several lakes e.g. Taro Co in the SW part of the plateau are through-flow lakes containing freshwater (salinity $<3\,\mathrm{g\,l^{-1}}$). Lakes in highly arid basins with little surface inflow may become hypersaline which is for instance the case of Chabyer Caka (Zabuye Lake) investigated by Wang et al. (2002) or Lagkor Co in the SW part of the Plateau. Salinity indeed influences the freezing and melting temperature of the lake water. The magnitude of the freezing point depression decreases with an increase of salinity. This leads in turn to shortening of ice cover period of salty lakes in comparison with freshwater lakes under the same condition i.e. climate, elevation etc.

Levels and extent of lakes on the TP experienced high oscillations as a reaction to changes in climate conditions in the past (Zhang and Liu, 2011; Phan et al., 2011; Kropáček et al., 2011b). Furthermore,the lake shore may have shifted for even hundreds of meters during the last 40 yr (Bianduo et al., 2009; Kropáček et al., 2011b). These oscillations were related to an increased runoff due to the retreat of mountain glaciers by Yao et al. (2007), who analyzed several catchments in Tibet. There is a lot of confusion in the terminology caused by parallel usage of several versions of names for the same lake. Often more than two versions are used in Tibetan while different transcriptions from Tibetan often via Chinese increase the confusion. Here we decided to adhere to a convention introduced by the Map of the lakes and glaciers on the TP (Yao, 2007) compiled by the Institute of TP Research, Chinese Academy of Science (ITP, CAS).

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3 Data and methods

3.1 MODIS instrument and data description

The study area features favorably low cloud cover during winter and spring periods and the data acquisitions by optical instruments are not hindered by polar darkness as it is the case for instance of high latitude Canadian lakes (Howell et al., 2009). Furthermore the medium resolution optical data, which have spatial resolution in the order of several hundred meters, allow for derivation of ice phenology for tens of lakes on the TP. This is in contrast to passive microwave data, with spatial resolutions in the order of tens of kilometers which are useful only for the largest lakes (Che et al., 2009). In this study we used MODIS data for the derivation of lake ice phenology of Tibetan lakes.

The Moderate Resolution Imaging Spectroradiometer (MODIS) instrument is carried by two polar orbiting satellites Terra and Aqua. The system is able to acquire data of the entire Earth's surface every 1 to 2 days in 36 spectral bands by both Terra (in the morning) and Aqua satellites (in the afternoon). In order to keep the data amounts at a reasonable level in this study we used the MODIS snow product MYD10A2 (Hall et al., 2007) instead of primary spectral bands. This product has a resolution of 500 m and is a composite classification image over a 8-day period based on a Normalized Difference Snow Index (NDSI) and several other criteria tests that minimizes the impact of cloud cover. The classification scheme matches the needs of this study as it contains following five classes: Snow, No snow, Lake, Lake ice and Cloud

3.2 Derivation of ice phenology dates from the MODIS 8-day composite data

The frozen lake surface is represented by classes Lake ice and Snow in the MODIS 8-day composites. We adopted the percentage of pixels classified as class water as a measure for the frozen status of the lake. This approach provides more accurate estimates than querying the number of pixels belonging to classes lake ice and snow since it accounts better for miss-registrations between MODIS scenes. For practical

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reasons a threshold for the ice/water extent had to be set in order to detect the ice phenology dates. Factors 5 % and 95 % for the area of open water were chosen as thresholds for the identification of the ice phenology events in order to exclude the influence of noise. Such absolute threshold would be insensitive to various disturbing effects. Instead we used an adaptive approach. The dataset was first divided by a median into two parts: one below median corresponding to frozen lake and the other one with the values above median corresponding to unfrozen conditions. In the next step mean values were calculated from both datasets. The thresholds 5 % and 95 % were then applied to the range limited by these calculated mean values instead of the whole range 0–100 %. This helped us to suppress the influence of mixed pixels, misclassification of shallow water as class 'No snow' and remaining discrepancies between the used lake outlines and the real shorelines.

For the extraction of ice phenology events from MODIS data lakes larger than 100 km^2 were selected. This resulted in 65 lakes which are well distributed over the TP (Fig. 1). Out of this group 6 lakes (Yinmar, Yamzhog Yumco, Nau Co, Gyeze Caka, Chabyer Caka and Ringinyububu Co) had to be sorted out since their histograms were too noisy for a reliable extraction of ice phenology. For instance the Yamzhog Yumco has highly complex tentacle-like shape that results in an extremely noisy signal. In order to account for regional differences in the ice regime of lakes in such a large area the lakes were divided into four regions Northwest, Northeast, Southwest and Southeast denoted by abbreviations NW, NE, SW, SE respectively (see Fig. 1). Mean values of DI, DCI, phenology dates and trends for these groups were calculated and compared.

Global Lakes and Wetlands Database – GLWD (Lehner and Döll 2004), which as a global dataset created as a combination of various available sources, was used for the definition of the spatial extents of the lakes. The shorelines from the GLWD were checked against the MODIS images. In some instances a certain amount of manual editing of the shoreline had to be involved i.e. shifts or shape adjustments. In order to account for small variations of the lake shapes caused by mixed pixels, a mean image was calculated from MODIS images covering autumn period after the monsoon and

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before the lake freeze-up. This image which shows in one layer spatial variations of shape between single acquisitions was used as a base layer for adjustments of the vector data. Another source of the size variation is probably a shoreline displacement connected to the lake volume/size oscillations (Bianduo et al., 2009; Wu and Zhu, 2008; Kropáček et al., 2011b) during the study period. These variations usually do not exceed the pixel size of MODIS.

In the next step histograms were extracted from all MODIS images in the time series separately for each lake. Graphs of percentage of open water area were constructed for the whole time period. The ice phenology events were then identified automatically as intersection of the curve representing open water with thresholds 5 % and 95 %. It was observed that multiple intersections with thresholds occur during the freeze-up and break-up period. This can occur due to ice retreat caused by wind events and refreezing during the break-up period or by cloud cover not accounted for by the 8-day compositing approach. Another reason is the presence of noise in the time series induced by classification uncertainty. The magnitude of the noise becomes evident as variation of the water curve during the summer period, which does not complement cloud cover.

In order to identify correctly the FU in case of multiple intersections of the open water curve with the threshold, which is mainly due to noise a point has been set well before possible early freeze up. From this point the first threshold crossing was searched for. Analogously all the other ice phenology dates were identified (Fig. 3). Since the points of the open water has 8-day sampling, the exact day of each ice phenology date was obtained as a linear interpolation of the first point below and above the threshold. All identified points representing the ice phenology dates were plotted together with the open water curve for a visual check.

3.3 Validation of open water area derived from MODIS 8-days composites

The accuracy of the derivation of the open water area for a lake from the MODIS 8-day composites was estimated by a comparison with a number of reference satellite

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images. These images cover various phases of freeze-up and break-up processes and they are from various satellite sensors including Envisat/ASAR (wide swath mode data), Landsat, TerraSAR-X and SPOT. For each validation image a percentage of the open water area was derived and compared with the water curve from MODIS 8-day data which was interpolated for each day. A time difference in days between each point representing the validation image and a corresponding point on the interpolated curve with the same percentage of open water was derived. An overall accuracy was then calculated as root mean square error of these time differences in days. A RMS error equal to 9.6 days was obtained from twenty validation images for Nam Co. Mean time difference as low as 1.2 days proves that there is no systematic error in the open water area estimation.

3.4 Correlation of the lake phenology with the local and climate factors

In an attempt to identify the main drivers of the ice regime of the study area the extracted ice phenology data was compared with data describing local and climate factors. The local factors which were possible to describe by available data were: latitude, longitude, elevation, area and shape. Latitude and longitude were retrieved from the GLWD using automatically generated centoids of lake polygons. The centroids were manually shifted inside the lake in several cases when they fell outside the lake polygons due to concave shape of the shore. Lake altitude was identified in the Shuttle Radar Topography Mission (SRTM) digital elevation model using the edited centroids. A simple shape index was defined as a ratio between perimeter and area, which can be easily retrieved from the GIS layer of lakes. This index describes shape complexity of the shore. Lakes with a complex shape are likely to have a lower depth and as a consequence a lower thermal inertia in comparison with a rounded lake of the same size. Lakes with high shape index are likely to provide more shallow bays where the freeze-up usually starts. Also the parameter lake area itself is a proxy of the lake volume and it is related to thermal inertia of the lake.

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For characterization of the climate for the selected lakes it is not possible to simply rely on measurements of nearby ground meteorological stations because of their sparseness. The density of stations decreases towards West, leaving the whole western part of the plateau with some five stations. To our knowledge only Nam Co and Gyaring Co have a ground meteorological station located in the immediate vicinity of its lake shore. Instead we rely on temperatures from the WorldClim database (Hijmans et al., 2005). This data set contains monthly precipitation and mean, minimum, and maximum temperature for the period from 1950 to 2000 interpolated to a 1 km grid. We used the maximum temperature and the calculated cumulative above zero temperature of the 1 km square identified by the lake polygon centroid for the characterization of the lake basin climate. Correlation coefficients were calculated between variables describing ice phenology and those describing the local and climate factors (see Table 3).

4 Results and discussion

The lake ice phenology for 59 lakes on the TP has been extracted from the time series of MODIS 8-day composites for the period from 2001 to 2010. This allowed us to get an overview of the regional differences in ice regime over the TP. DCI and DI feature a high variation amongst the four geographical regions (Tab. 1). This means that any general figures for the whole TP would not be representative. For several lakes it was not possible to extract the ice phenology due to a high level of noise in the signal obtained from the MODIS 8-day composites. This was most likely due to the effect of mixed pixels. This effect impacts more strongly smaller lakes and lakes with complex shape. Since the lower limit of the used method in terms of lake size is shape dependant, it would be difficult to set a threshold of certain minimal lake size as a clear limitation of the method. In the case of some lakes open water was mis-classified as class land in the MODIS 8-day composites, which can be probably explained by a high sediment load in the water, for instance Ulan Ul Lake.

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4.1 Duration of ice cover for lakes in the four regions

There is a difference in the ice cover duration in terms of both DCI and DI for the studied regions (Table 1). The most remarkable difference can be seen between the southern and the northern regions which indeed corresponds to the gradient in the Earth surface irradiation with the decreasing latitude. The studied lakes span over a latitude difference of around 10 degrees. The difference in DCI between the corresponding southern and northern regions amounts approximately one and half months. The gradient in the west-east direction is much lower as the difference in DCI between the two northern and the two southern regions amounts for two weeks and in DI only 6 and 13 days respectively.

The northern regions feature higher variations in both the DCI and the DI. This is due to a higher differences in altitude of the lakes. Each of these two regions contains one lake of distinctly lower altitude Ayakkuh Lake (4261 m a.s.l.) in the NE region and Bangong Co (4227 m a.s.l.) in the NW region. Another reason for the lower variation in the lake ice cover duration in both of the southern regions is the distribution of the lakes along a parallel decreasing the range of latitude. The difference between the DI and DCI for all the studied lakes is on average 49 days which corresponds to the sum of mean durations of freeze-up and break-up periods.

4.2 Trends in duration of ice cover in the four regions

Trends in DCI and DI for all regions were fitted to mean values calculated for every year (Fig. 6). They are listed together with the corresponding standard deviations in (Table 2). The standard deviations reveal the magnitude of differences in the behavior of lakes in each group. The especially high standard deviation in case of group NE suggests that there is a strong influence of the local factors on the ice regime of lakes in this region. There are differences between the trend in DCI and the trend in DI for the same region. This reflects variation in duration of the freeze-up and break-up periods and it is also highly influenced by no complete freeze-up events. The differences in

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duration of the freeze-up and break-up periods may be caused by snow fall and wind events, isolating effect of snow cover slowing up the break-up, changes in albedo etc. Both northern regions appear to have negative trends in both DCI and DI. The duration of the ice cover decreases rapidly for one to two and half days per year on average. Both the northern regions on the contrary feature a positive trend in both variables. However apart from the SE region the variations are exceeding the calculated trend.

4.3 Validation of the no complete freeze-up events

It appears that there was no complete freeze-up in some years for several lakes. This may be surprising in an area with harsh climate and with a long period of below 0 °C temperatures. This occurs also in the case of some large lakes like for instance Taro Co. In order to exclude the possibility that the phenomena is only random noise in the data, quick-looks of Landsat scenes were checked for the presence of open water in the relevant periods. The presence of open water during usual ice-on season was confirmed in this way for a number of lakes (see Table 3).

4.4 Results for the four geographic regions

4.4.1 Region Northeast

This group contains in total fifteen lakes out of which five are larger than 300 km^2 (Table A1). The ice regime of lakes in this region is determined by cold continental climate with annual mean below −2 °C (Fig. 2). These climatic conditions are reflected by a long duration of ice cover (DCI 131.6 days and DI 180.2 days). There is a high variation of both DCI and DI (Table 1). A large range of elevations in this group, which is more than one thousand meters (Table 1) and a large range of latitude are indeed important factors that contribute to this high variation of ice cover duration. Lake Ayakkuh features remarkably short mean DI of 88.3 days in comparison with the average DI of the group mainly due to its low elevation (4161 m a.s.l.). Lakes Xijir Ulan, Yaggain

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Canco and Dogai Coring did not freeze up completely during the seasons 2001 and 2002.

The trend in duration of lake ice period is positive in terms of both DCI and DI (Table 2) and amounts for 2.5 and 3.0 days yr^{-1} respectively. However there is a high variation of trend in both the DI and DCI (Table 2). Eight lakes of the group have a positive trend of DI while for the rest of the lakes it is negative. Four lakes in this region appear to have a rapid increase in the ice cover duration in terms of the DI: Dogai Coring, Xijir Ulan, Ayakkuh Lake, Lixi Oidaim Co and Yaggain Canco. All of these lakes have also a high variation in ice cover duration (Table A1). In the case of Dogai Coring, a Xijir Ulan and Yaggain Canco, both the increasing trend and the high variation are strongly impacted by occurrence of no freeze-up events in the studied period.

4.4.2 Region Northwest

This group is located in the very western part of the TP bordered from the north by the Kunlun Mountains and it contains fourteen lakes with an altitude range of 840 m (Table B1). The lowest and the largest lake is Bangong Co at the Indian border with an elongated shape. On average lakes in this region feature a long ice cover period: DCI 118.0 and DI 186.4 days with the highest variability in comparison with the other groups (Table 1). Two lakes: Bangong Co and Gyeze Caka did not freeze-up completely during the whole period from 2001 to 2010. In addition Longmu Co has very short duration of ice cover both in terms of DI and DCI and in some seasons did not freeze-up completely. Gyeze Caka even appeared ice free with no signs of freezing up during the studied period. The reason could be the depth in the case of Bangong Co given as 42.3 m by Yao (2007) and the hypersalinity in the case of Gyeze Caka (caka means salty lake in Tibetan). It is indeed also due to the influence of these three lakes that the variation of ice cover in this group is high (Table 1). Other factors are a relatively high altitude range and likely also differences in salinity and depth. The shortest ice cover in this group appart of Gyeze Caka has Longmu Co with the mean DI of only 94.9, while the longest ice cover of 241 days was observed in two lakes: Bairab Co (4952 m a.s.l.) and Gozha Co (5070 m a.s.l.).

There is a positive trend in the ice cover duration in terms of both DCI and DI which is 3.1 and 1.0 days y^{-1} respectively (Table 2). The overall positive trend given in lake ice cover duration does not seem to be representative, taking into account the high variation of the trend between the lakes and the fact that six lakes of the group have a negative trend in DI (Table B1). The positive trend in DCI is also highly influenced by the high trend of two lakes: Aksayqin and North Heishi with extremely low values of DI in 2001 and 2003.

4.4.3 Region Southwest

Lakes in this region are distributed approximately along the parallel 30° N and this lake pattern continues towards the East in the SE region (Fig. 1). The border between regions SE and SW was thus decided arbitrarily in order to obtain groups of comparable lake numbers and also to allow the comparison of lake ice phenology along the East–West direction. This region has fourteen lakes (Table C1) including many of the largest lakes on the TP e.g. Zhari Namco, Ngangla Ringco, Tangra Yumco and Taro Co. Except for Mapam Yumco and La'nga Co all lakes are in the central part of the plateau north from Gangdise Mountains, which acts as a barrier to monsoon circulation. Both Mapam Yumco (Manasarowar Lake) and La'nga Lake are freshwater lakes. These lakes are connected by surface stream forming together an endorheic system, but it seems that in the past they drained towards the west to Sutlej River Basin.

The lake ice cover in this region with an average DCI of 67.6 days and a DI of 127.7 days is the shortest of the four regions. Lakes Taro Co, Tangra Yumco, Paiku Co, Xuru Co, Monco Bunyi and Dajia Co did not freeze up completely in some years. Tangra Yumco, which is regarded as the deepest lake on the TP (Wang et al., 2010), is divided into northern and southern parts by a narrow strait. The northern part freezes over later or not at all as seen on Landsat images (for instance on 31 March 2007, 27 February 2008 and 15 March 2010). This is obviously caused by a heat accumulation in the northern part that reaches a depth of 214 m which is circa 100 m deeper than the southern part (Wang et al., 2010). In the case of Taro Co, the influence of high salinity on this effect can be excluded since this lake while having an outlet towards Chabyer Caka is a fresh water lake (Wang et al., 2002). The DI of lakes in this region varies from 59.2 days (Paiku Co) to 179.9 days (Palung Co). In case of Paiku Co it was only in 2008 that it froze over completely. The mean trend in ice cover duration of this group of lakes is negative indicated by both DCI and DI with a relatively low variation in DI (Table 2). Mean trend in DCI and DI reach −1.8 and −1.1 days yr^{-1} respectively. All but three lakes have negative trend in DI. This would suggest that there is a significant trend in DI in the region but the variation of trend amongst the lake of the group exceeds the trend.

4.4.4 Region Southeast

This group of sixteen lakes includes the two largest lakes Nam Co and Serling Co (Table D1). Apart from Puma Yumco, which is an isolated lake further in the SE, the lakes of this group are located in the central part of the plateau north from the Gangdise and Nyainqentanglha Mts. The lakes in this region span an elevation range of 560 m a.s.l. with a mean elevation of 4608 m a.s.l. Although the mean elevation is lower in comparison with the SW region the ice cover is longer (DCI of 92.4 days and a DI of 140.4 days). It is probably due to a lower mean temperatures (Fig. 2). The low altitude range is likely one of the reasons for the lowest variation of ice cover duration in comparison with the other regions (Table 1). Pangkog Co, which is located immediately to the east from Serling Co, has the longest lake ice period. This anomalous behavior cannot be explained by a high elevation, while with the altitude of 4529 m a.s.l. it is the third lowest lake of the group. A possible explanation would be a relatively small size of 100.7 km^2 combined with a high salinity and a low depth. Unfortunately, no bathymetry measurements are available. Several lakes in this region do not freeze over completely during some seasons, for instance Bam Co in 2009, Npen Co in 2006 and Ringco Ogma in 2006. All but two lakes have negative trend in DI which is on average −2 days yr^{-1} in this group

(Table 2). This would again suggest that there is a significant trend in DI in the region but the variation of trend amongst the lake of the group is still high.

4.5 Correlation of ice phenology variables with climatic and local parameters

Statistical analysis of the dependency of ice phenology variables on climatic and local parameters was carried out for all 59 studied lakes (Table 4). In order to assess the sensitivity of the analysis to lake selection and to suppress the influence of noise introduced by mixed pixels, which obviously play a more important role in the case of smaller lakes, the same analysis was repeated for lakes larger than 300 km^2 (18 lakes in total (Table 5)). Results of the analysis showed that there is a high correlation of ice cover duration (DCI and DI) with temperature. Both mean temperature and cumulative temperature above 0 °C derived from Worldclim database feature a high correlation coefficient from 0.63–0.69. The selection of lakes larger than 300 km^2 leads to a increase of the correlation coefficient to 0.78 to 0.89. In both cases the cumulative temperature features higher values of the correlation coefficient. This confirms high thermal determination of lake phenology reported by many studies for a number of lakes worldwide. The dependency of ice phenology on thermal variables would be likely higher if the freezing point depression caused by salinity could have been taken into account.

High correlation of ice cover duration ($r > 0.41$) with latitude is in fact related to decrease of temperature towards the North due to a lower total irradiation and due to continental climate. There is probably no strong driver of the ice regime, which would lead to an East–West gradient in ice phenology since only a weak correlation was revealed between the ice phenology variables and longitude. Ice cover duration appears to change with altitude due to a decrease of temperature connected to decrease of air pressure which can be expressed by temperature lapse rate. The selection of the large lakes leads to a significant increase of dependency of ice cover duration to altitude. This can be likely caused by an inaccuracy in determination of lake ice phenology dates for smaller lakes with noisy time series of the satellite data classifications.

While there is only a weak correlation of ice phenology variables with the perimeter/area index for all lakes there is a strong correlation for the selected large lakes achieving $r = 0.79$ in case of duration of complete ice cover (DCI). This shows that the shape complexity significantly affects the ice phenology in particular the freeze-up process providing shallow bays for the development of an early ice. On the contrary the break-up process seems to be largely unaffected by the shape complexity even in the case of the large lakes. The lower correlation of the perimeter/area index with ice phenology variables for all lakes than to the lakes >300 km^2 may be due to generalized shapes of lake shorelines in the GLWD database, which may affect the smaller lakes more. Only a weak correlation with ice phenology variables was calculated for the parameter area. This suggests that a large area does not always mean a large depth respective volume and thermal capacity.

The analysis revealed much higher dependency of FO and WCI to the climate and local parameters than in case of FU and BU. This can be caused by two factors. Either wind or the local conditions lead to a higher variation of FU and BU, but don't affect the same way the FO and WCI; or, the spatial variation of BU and FU is purely caused by systematically higher inaccuracy in BU and FU estimation. Whatever the reason, the FO and WCI (respective DI as their difference) derived from MODIS 8-day snow composites appears to be a better indicator for changes in climate on the TP. While comparing the correlation of BU and FU with temperature, it is the FU that appears to be more thermally determined, which contradicts to findings of Duguay et al. (2006) who found the BU to be the more robust indicator of climate oscillations than FU in case of Canadian lakes.

5 Conclusions

Ice phenology was derived for 59 lakes on the TP from MODIS 8-day composite data. The obtained results imply that despite some influence of local settings e.g. salinity, shape or wind exposure, the ice phenology of Tibetan lakes is to a high degree

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determined by climate, especially the air temperature which is in agreement with results from other cold regions of the world. This suggests that changes in ice phenology of Tibetan lakes can indicate variations in regional climate. This is highly valuable since the area is only sparsely covered by ground observations and at the same time plays an important role in regional and global climate. The ice phenology of the studied lakes averaged over the acquisition period features a high variation both in the regions and while comparing them. This reflects differences in geographical location such as altitude and latitude, local settings and probably also differences in salinity, which could not be checked due to the unavailability of reference data. This study showed that a number of Tibetan lakes do not freeze up completely during some winter seasons. This interesting phenomena and its consequences for local climate including snow cover regime should be paid a proper attention in further research. Both of the variables, used as measure of duration of the ice cover, DI and DCI can be used as a climate indicator, although DI appeared to be more stable in terms of variation in three of the four regions than DCI. Additionally the estimation of DCI is hindered when the lakes do not freeze up completely. It can be thus concluded that DI allows more reliable characterization of the ice regime from MODIS 8-days composites for lakes on the TP. It appears, that FO and WCI are more thermally determined than FU and BU in case of the studied lakes.

It has been observed that cumulative above 0 °C temperature averaged over the period from 2001 to 2010 represents a better proxy for the lake ice regime than the annual maximum temperature. This indicates that cumulative above zero temperature is a better proxy of the accumulation of energy in water mass which is an important driver of the freeze-up process. This lake-atmosphere interaction may have some additional effects on the local climate during the cold part of the year, for instance by complex mechanisms of lake effect snow fall during Autumn.

The available time series of MODIS data allowed us to derive a trend in ice cover duration for the studied lakes, which appeared highly variable over the TP. The high variation remains even after the derivation of mean values for the geographically compact

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regions. These facts together with the relatively short evaluation period of ten years would make any general conclusion about a trend in ice phenology on the TP dubious. For the extraction of a trend significant for the assessment of changes in climate on the TP a longer time series of observations would be needed.

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Table 1. Duration of complete ice cover (DCI) and duration of ice cover (DI) in days calculated as a mean value for each of the four geographical regions over the period from 2001 to 2010 and standard deviations (σ) of both the variables, which is a measure of variation of ice cover amongst the lakes in each group.

region	mean altitude (m)	altitude range(m)	DCI	DI	σ of DCI	σ of DI
NW	4850	840	118.0	186.4	68.6	69.0
NE	4714	1060	131.6	180.2	55.7	52.9
SW	4731	660	67.6	127.7	47.7	38.2
SE	4608	560	92.4	140.4	26.8	22.1

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Table 2. Trends in days/year in DCI – duration of complete ice cover and DI – duration of ice cover in the period from 2001 to 2010 for each group determined as a trend of mean values calculated for every year. The corresponding standard deviations of trends gives an idea about the variation of trends in each region.

region	Trend DCI	σ trend DCI	Trend DI	σ trend DI
NW	3.1	5.4	1.0	2.6
NE	2.5	4.4	3.0	5.5
SW	−1.8	4.9	−1.1	1.8
SE	−2.4	2.0	−2.3	2.1

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Table 3. Validation of the no complete freeze-up events detected by MODIS data for selected lakes by Landsat data. Percentage of ice cover was determined from available Landsat images falling to the period of usual ice cover determined for the particular region.

Lake name (region)	Ice Cover from Landsat, Dates (% of ice cover from Landsat TM and ETM+)	Mean FU from MODIS (region)	Mean BU from MODIS (region)	Seasons of no complete freeze-up from MODIS
Taro Co (SW)	6/2/09 (40 %), 15/2/2009 (60 %), 3/3/2009 (60 %), 2/2/10 (30 %), 18/2/10 (80 %), 6/3/10 (90 %)	18 Jan (7 Jan)	24 Jan (15 Apr)	2003-5, 2008-10
Tangra Yumco (SW)	11/02/2010 (5 %), 27/02/2010 (40 %), 15/03/2010 (40 %)	21 Jan (7 Jan)	6 Feb (15 Apr)	2003, 2005-7, 2009-10
Nam Co (SE)	5/2/2001 (70 %), 26/4/2001 (60 %)	13 Feb (27 Dec)	4 Apr (29 Mar)	2001, 2009
Xijir Ulan (NE)	16/3/2001 (20 %), 19/3/2002 (20 %), 23/3/2003 (20 %), 23/2/2005 (20 %)	29 Dec (7 Dec)	25 Jan (18 Apr)	2001-3, 2005-6
Bangoing Co (NW)	22/2/2004 (0 %), 7 Jan 2005 (60 %), 28/3/2005 (0 %), 2/3/2010 (10 %)	(8 Dec)	(14 Apr)	2001-10

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Table 4. Correlation of ice cover duration (DCI – duration of complete ice cover and DI – duration of ice cover) and ice phenology dates with climate and local parameters calculated for all 59 studied lakes. Correlation coefficient exceeding 0.5 is in bold numbers.

	DCI	DI	FO	FU	BU	WCI
longitude (deg)	0.21	0.17	−0.31	0.05	−0.04	**−0.63**
latitude (deg)	0.52	0.47	−0.51	0.34	0.13	**−0.63**
altitude (m a.s.l.)	0.41	0.46	−0.27	0.22	0.19	**0.65**
t cumul (°C)	**−0.68**	**−0.69**	**0.59**	−0.30	−0.23	**0.65**
t max (°C)	**−0.63**	**−0.63**	**0.53**	−0.30	−0.20	**0.57**
perim/area	0.19	0.15	−0.27	0.12	0.03	0.11
area (sq. km)	−0.31	−0.22	0.29	−0.20	0.00	−0.02

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Table 5. Correlation of ice cover duration (DCI – duration of complete ice cover and DI – duration of ice cover) and ice phenology dates with climate and local parameters calculated for lakes larger than 300 km^2 (18 largest lakes). Correlation coefficient exceeding 0.5 is in bold numbers.

	DCI	DI	FO	FU	BU	WCI
longitude (deg)	0.28	0.29	−0.33	0.18	0.11	**−0.63**
latitude (deg)	0.46	0.45	**−0.63**	**0.52**	0.16	**−0.63**
altitude (m a.s.l.)	**0.75**	**0.73**	**−0.54**	0.36	0.31	**0.50**
t cumul (°C)	**−0.84**	**−0.89**	**0.81**	−0.47	−0.32	**0.50**
t max (°C)	**−0.78**	**−0.80**	**0.69**	−0.47	−0.28	0.38
perim/area	**0.79**	0.49	−0.49	0.43	0.26	−0.05
area (sq. km)	−0.32	−0.27	0.31	−0.07	0.14	−0.08

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Table A1. Derived lake ice phenology for lakes in the group NE.

name	Elevation (m a.s.l.)	label in Fig. 1	trend in DCI	trend in DI	mean DCI (days)	σ of DCI	mean DI (days)	σ of DI	mean FO	mean FU	mean BU	mean WCI
Yaggain Canco	4872	45	8.9	15.5	117.0	51.3	136.8	55.0	1 Dec	6 Dec	2 Apr	17 Apr
Dorsoidong Co	4929	46	−0.9	−0.6	146.9	6.5	180.8	10.4	22 Nov	7 Dec	3 May	22 May
Migriggyangzham	4935	47	−4.3	−1.9	131.5	27.0	194.2	13.4	18 Nov	4 Jan	16 May	31 May
Dogai Coring	4818	48	2.5	7.3	33.4	30.7	90.8	40.8	31 Dec	1 Jan	4 Feb	1 Apr
Aqqik Kol	4251	49	2.4	1.2	140.6	12.3	176.4	8.0	16 Nov	28 Nov	18 Apr	11 May
Ayakkuh Lake	3876	50	4.6	4.0	41.5	18.9	88.3	15.0	16 Dec	3 Jan	14 Feb	15 Mar
Jingyu	4713	51	3.3	−0.4	176.9	18.9	211.1	7.1	7 Nov	23 Nov	20 May	7 Jun
Lixi'Oidaim Co	4870	52	7.5	7.2	124.7	25.9	171.6	28.5	15 Nov	9 Dec	12 Apr	5 May
Xijir Ulan Lake	4772	53	−5.5	13.1	26.7	36.7	102.8	60.3	24 Dec	29 Dec	25 Jan	6 Apr
Ulan Ul Lake	4855	54	3.4	−0.3	166.0	35.9	237.9	14.2	21 Oct	26 Nov	11 May	16 Jun
Taiyang	4881	55	−0.6	−2.8	188.2	13.1	213.6	12.9	16 Nov	30 Nov	7 Jun	18 Jun
Hoh Xil Lake	4886	56	−6.2	2.5	195.0	34.0	249.9	15.5	20 Oct	15 Nov	29 May	27 Jun
Huiten Nur	4753	57	−1.6	1.2	184.9	10.9	228.0	19.6	25 Oct	24 Nov	28 May	10 Jun
Dorge Co	4688	58	1.9	−0.1	144.8	29.1	221.9	9.4	17 Oct	22 Nov	17 Apr	27 May
Hoh Sai Lake	4475	59	−1.2	−0.4	156.6	6.0	199.5	11.0	4 Nov	2 Dec	8 May	23 May

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Table B1. Derived lake ice phenology for lakes in the group NW.

name	Elevation (m a.s.l.)	label in Fig. 1	trend in DCI	trend in DI	mean DCI (days)	σ of DCI	mean DI (days)	σ of DI	mean FO	mean FU	mean BU	mean WCI
Aksayqin	4844	1	10.5	2.1	106.3	57.1	192.2	12.1	8 Nov	3 Dec	20 Mar	19 May
Chem Co	4961	2	0.2	−1.4	145.3	19.7	197.4	10.6	13 Nov	28 Nov	22 Apr	30 May
Bangong Co	4239	3	0.0	1.0	0.0	0.0	125.4	15.6	17 Dec	1 Jan	1 Jan	21 Apr
Longmu Co	5004	4	−3.6	7.5	24.1	32.3	94.9	30.5	11 Jan	16 Jan	9 Feb	16 Apr
Gozha Co	5080	5	2.4	2.0	165.6	16.3	240.9	19.0	9 Nov	28 Dec	12 Jun	8 Jul
Geyze Caka	4525	6	–	–	0.0	0.0	0.0	0.0	–	–	–	–
Bamgdog Co	4904	7	2.6	2.8	169.1	21.6	219.8	16.3	4 Nov	25 Nov	14 May	11 Jun
Lamaqangdong	4812	8	−1.6	−0.4	153.3	9.7	204.6	14.8	15 Nov	8 Dec	10 May	7 Jun
Memar Co	4920	9	−0.7	−0.3	169.1	15.0	232.8	13.2	26 Oct	19 Nov	8 May	16 Jun
Aru Co	4937	10	−1.2	−0.2	51.8	52.9	176.5	21.7	16 Nov	26 Dec	16 Feb	11 May
Heishi	5049	11	12.9	−1.0	160.2	55.7	228.6	9.1	5 Nov	2 Dec	11 May	22 Jun
Jianshui	4889	12	−2.1	−3.5	190.9	24.3	230.9	15.1	21 Oct	17 Nov	26 May	9 Jun
Bairab	4960	13	−0.4	0.7	169.7	37.1	241.0	14.6	23 Oct	3 Dec	22 May	21 Jun
Yang	4778	14	8.3	0.0	146.1	62.7	224.4	16.6	29 Oct	27 Nov	22 Apr	10 Jun

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Table C1. Derived lake ice phenology for lakes in the group SW.

name	Elevation (m a.s.l.)	label in Fig. 1	trend in DCI	trend in DI	mean DCI (days)	σ of DCI	mean DI (days)	σ of DI	mean FO	mean FU	mean BU	mean WCI
Langa Co	4570	15	−0.2	2.1	60.8	35.1	154.3	25.5	10 Dec	25 Jan	27 Mar	13 May
Mapam Yumco	4585	16	−5.6	−4.2	71.6	23.5	114.9	16.7	9 Jan	2 Feb	15 Apr	5 May
Ngangla Ringco	4716	17	−0.7	−1.0	109.2	8.3	167.0	16.9	18 Nov	24 Dec	12 Apr	4 May
Palung Co	5101	18	−2.0	−1.5	144.3	16.9	179.9	17.2	16 Nov	3 Dec	27 Apr	15 May
Taro Co	4567	19	−2.5	0.2	6.0	8.9	102.4	10.9	12 Jan	18 Jan	24 Jan	24 Apr
Dawa Co	4623	20	0.7	−2.1	124.8	5.3	172.3	15.5	12 Nov	10 Dec	14 Apr	4 May
Zhari Namco	4612	21	0.8	−0.1	83.3	9.4	121.8	7.8	16 Dec	4 Jan	29 Mar	17 Apr
Geysa Co	5198	22	−9.5	−2.7	101.1	40.7	156.0	31.9	6 Dec	16 Jan	27 Apr	12 May
Dajia Co	5145	23	−3.4	−0.4	97.4	44.0	155.8	31.0	29 Nov	31 Dec	8 Apr	4 May
Paiku Co	4580	24	0.0	−4.0	3.8	12.0	59.5	26.7	3 Feb	6 Jan	10 Jan	4 Apr
Monco Bunnyi	4684	25	10.7	−0.1	30.6	37.3	106.8	21.4	24 Dec	17 Jan	17 Feb	10 Apr
Xuru Co	4714	26	0.0	1.2	5.2	8.6	69.1	15.9	1 Feb	9 Feb	15 Feb	12 Apr
Tangra Yumco	4535	27	3.0	−1.9	16.0	21.9	95.1	12.4	13 Jan	21 Jan	6 Feb	18 Apr
Ngangzi Co	4685	28	−1.2	−1.2	92.3	13.3	132.6	8.1	26 Nov	9 Dec	11 Mar	8 Apr

Table D1. Derived lake ice phenology for lakes in the group SE.

name	Elevation (m a.s.l.)	label in Fig. 1	trend in DCI	trend in DI	mean DCI (days)	σ of DCI	mean DI (days)	σ of DI	mean FO	mean FU	mean BU	mean WCI
Ngangzi Co	4685	28	−1.2	−1.2	92.3	13.3	132.6	8.1	26 Nov	9 Dec	11 Mar	8 Apr
Dogze Co	4465	29	−0.7	−1.7	104.6	7.7	132.2	9.7	6 Dec	16 Dec	31 Mar	18 Apr
Urru Co	4554	30	−1.6	0.1	57.0	23.8	116.4	7.9	31 Dec	20 Jan	18 Mar	26 Apr
Gyaring Co	4649	31	−0.6	−1.2	76.0	21.0	113.2	8.8	30 Dec	18 Jan	4 Apr	22 Apr
Co Ngoin	4563	32	1.1	−2.9	89.3	26.8	126.0	28.8	29 Nov	26 Dec	25 Mar	4 Apr
Serling Co	4539	33	−1.7	−3.0	91.3	9.5	142.0	12.5	4 Dec	3 Jan	5 Apr	25 Apr
Pangkog Co	4527	34	−0.8	−5.6	150.5	6.9	204.8	19.8	23 Oct	17 Nov	17 Apr	16 May
Ringco Ogma	4656	35	−5.7	−3.9	65.8	50.1	152.6	18.0	25 Nov	30 Dec	6 Mar	27 Apr
Puma Yumco	5013	36	−3.3	−1.1	106.0	27.6	128.2	8.7	28 Dec	12 Jan	28 Apr	6 May
Nam Co	4724	37	0.4	−3.2	50.3	29.4	130.8	12.4	4 Jan	13 Feb	4 Apr	15-May
Bam Co	4560	38	−5.2	−0.6	73.3	41.6	132.2	12.2	6 Dec	9 Jan	22 Mar	17 Apr
Npen Co	4666	39	−2.7	2.8	84.7	31.3	130.5	17.8	22 Dec	10 Jan	05 Apr	1 May
Pung Co	4529	40	−2.7	−2.9	87.9	28.8	128.3	15.2	8 Dec	25 Dec	23 Mar	16 Apr
Dung Co	4551	41	−4.5	−5.3	110.0	19.2	160.5	22.7	4 Nov	8 Dec	28 Mar	14 Apr
Co Nag	4585	42	−4.1	−3.5	80.7	23.8	140.9	22.5	14 Nov	11 Dec	2 Mar	4 Apr
Zige Tangco	4568	43	−3.0	−2.4	123.7	10.1	145.6	8.3	1 Dec	10 Dec	13 Apr	26 Apr
Kyebxang Co	4615	44	−1.7	−2.1	127.2	7.8	161.6	7.7	22 Nov	6 Dec	13 Apr	3 May

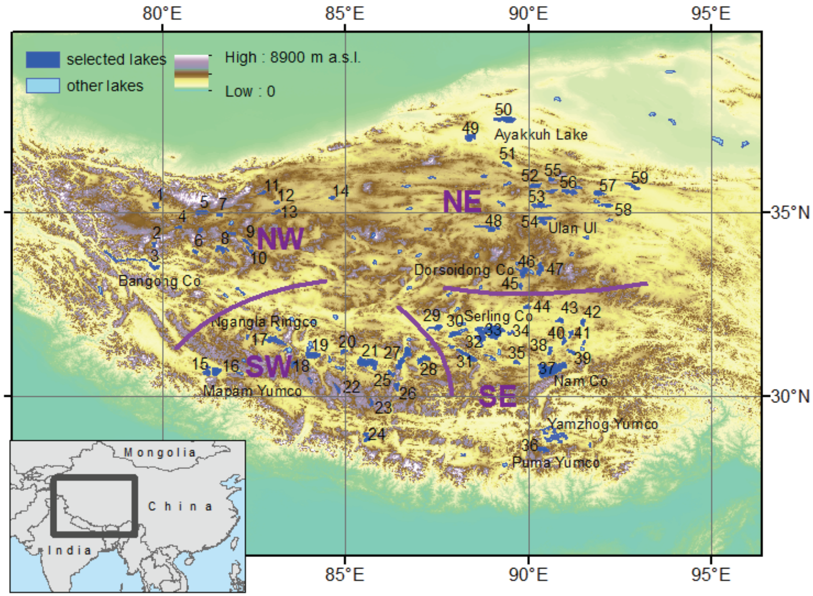

Fig. 1. Study area divided into four regions NW, SW, SE and NE. Selected lakes are highlighted. ***Region NW:*** 1 Aksayqin, 2 Chem Co, 3 Bangong Co, 4 Longmu Co, 5 Gozha Co, 6 Geyze Caka, 7 Bamgdog Co, 8 Lumaqangdong Co, 9 Memar Co, 10 Aru Co, 11 North Heishi, 12 Jianshui, 13 Bairab, 14 Yang; ***Region SW:*** 15 Langa Co, 16 Mapam Yumco, 17 Ngangla Ringco, 18 Palung Co, 19 Taro Co, 20 Dawa Co, 21 Zhari Namco, 22 Geysa Co, 23 Dajia Co, 24 Paiku Co, 25 Monco Bunnyi, 26 Xuru Co, 27 Tangra Yumco, 28 Ngangzi Co; ***Region SE:*** 29 Dogze Co, 30 Urru Co, 31 Gyaring Co, 32 Co Ngoin, 33 Serling Co, 34 Pangkog Co, 35 Ringco Ogma, 36 Puma Yumco, 37 Nam Co, 38 Bam Co, 39 Npen Co, 40 Pung Co, 41 Dung Co, 42 Co Nag, 43 Zige Tangco, 44 Kyebxang Co; ***Region NE:*** 45 Yaggain Canco, 46 Dorsoidong Co, 47 Migriggyangzham Co, 48 Dogai Coring, 49 Aqqik Kol, 50 Ayakkuh Lake, 51 Jingyu, 52 Lixi'Oidaim Co, 53 Xijir Ulan Lake, 54 Ulan Ul Lake, 55 Taiyang, 56 Hoh Xil Lake, 57 Huiten Nur, 58 Dorge Co, 59 Hoh Sai Lake.

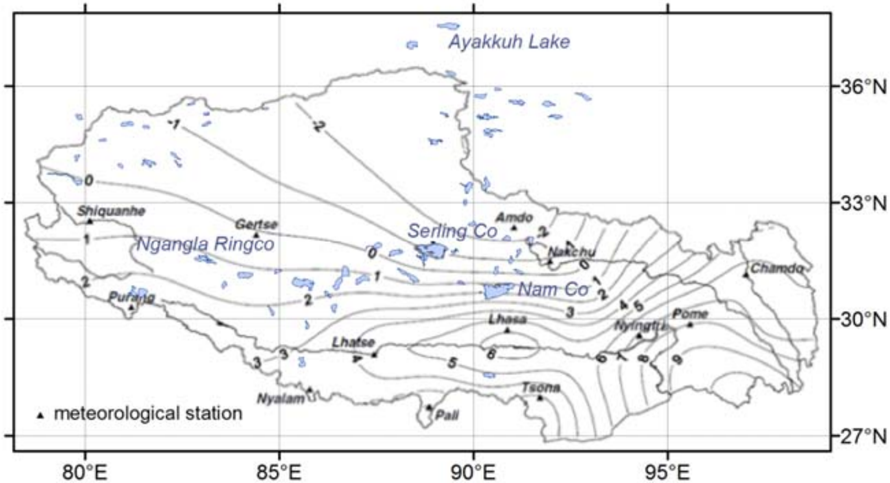

Fig. 2. Contours of mean temperature in the Tibet Autonomous Region (after Xu et al., 2008).

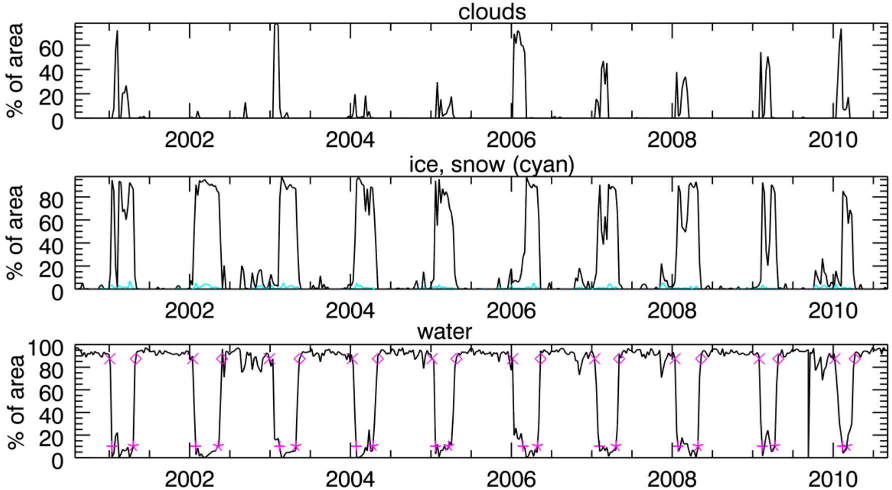

Fig. 3. An example of curves for open water (below), ice and snow (middle) and clouds (above) derived from MODIS 8-days composite data for Mapam Yumco (Lake Manasarowar). The identified lake ice phenology events are marked with symbols: "x" for FO, "+" for FU, "*" for BU and "◇" for WCI. The noise in the total ice cover is often caused by confusion with clouds which are actually rare in the winter period on the TP.

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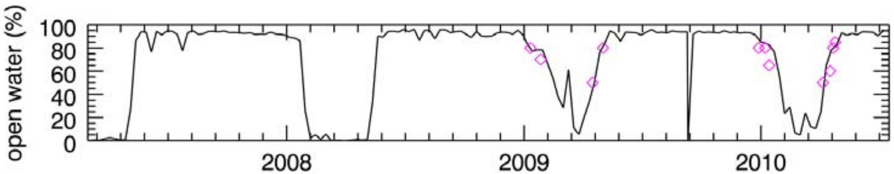

Fig. 4. Validation of the time series representing the area of open water for Nam Co derived from MODIS 8-day composite data by comparison of the open water curve with points representing the area of open water extracted from high resolution satellite images (Landsat, Envisat/ASAR, TerraSAR-X and SPOT).

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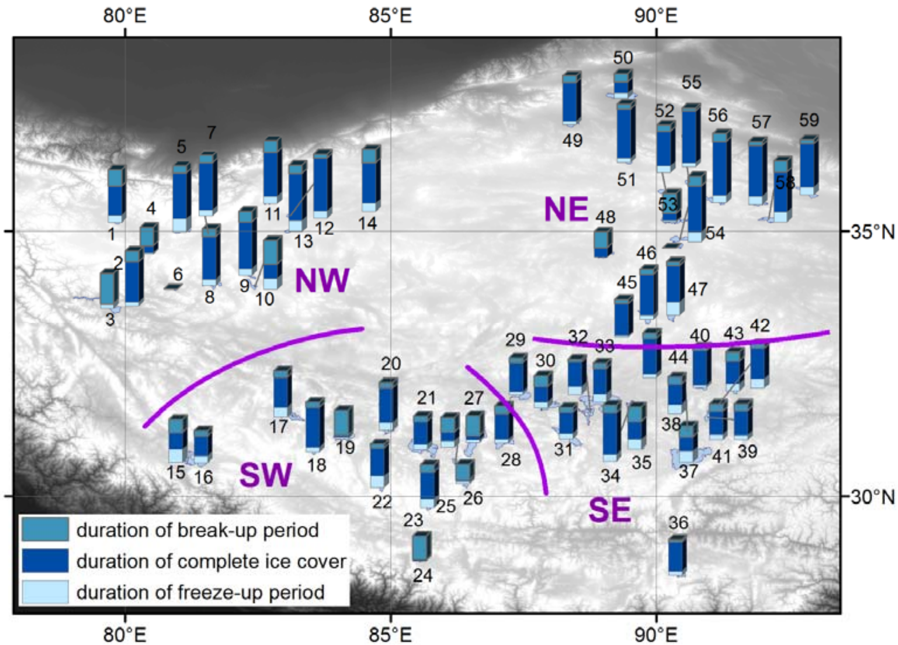

Fig. 5. Ice cover duration for the studied lakes on the TP showing duration of freeze-up period, duration of complete ice cover (DCI) and duration of break-up period as heights of the respectively colored sections of bar symbols whereas the total size of the bar represents the duration of ice cover (DI).

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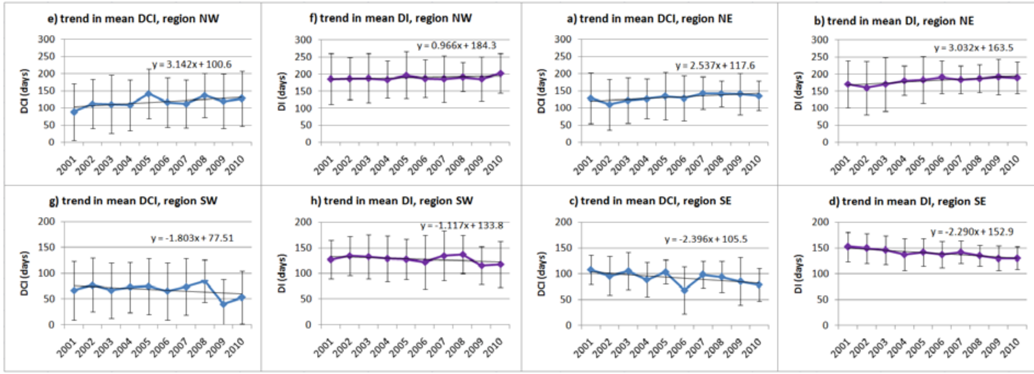

Fig. 6. Trends in the lake ice cover duration in terms of DCI and DI for all four regions.

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