Relationship between glacier melting and atmospheric circulation in the southeast Siberia

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Abstract. The interaction between climate and cryosphere is a key issue in recent years. Changes in surface mass balance of mountain glaciers closely correspond to differential changes in atmospheric circulation. Mountain glaciers in southeast Siberia located on East Sayan, Baikalsky and Kodar ridges have been continuously shrinking since the end of the Little Ice Age. In this study we used daily synoptic weather maps (Irkutsk Center of Hydrometeorology and Environmental Monitoring), 500 hPa, 700 hPa and 850 hPa geopotential height and air temperature data of NCEP/NCAR reanalysis to assess relationships between atmospheric circulation patterns and the sum of positive temperature (SPT), a predictor of summer ice/snow ablation. Results show that increased SPT (ablation) is generally associated with anticyclones and anticyclonic pressure fields (with cloudless weather conditions) and warm atmospheric fronts. Decreased SPT (ablation) is strongly correlated with cyclones and cyclonic type pressure fields, cold atmospheric fronts and air advections. Significant correlations have been found between ablation and cyclonic/anticyclonic activity. Revealed decreasing trends in the SPT in three glaciarized ridges at the beginning of the 21st century led to changes of air temperature and snow/ice melt climates.

1. Introduction
Atmospheric circulation is a basic climate factor and the problem of interaction between atmosphere and cryosphere at global and regional levels is still up to date. Mountain glaciers are good indicators of such interaction at global, regional and local scales. It should be noted that response of inland glaciers to climate change is studied insufficiently. Typical examples of such glaciers are mountain glaciers of the south of Eastern Siberia, located in high-mountain environments of East Sayan, Baikalsky and Kodar ridges [1]. The atmospheric circulation patterns controlling energy fluxes at glacier surfaces operate under combination of such factors as difficult orography and remoteness from oceanic atmosphere centers of action. The studies of relationships between the glacier mass-balance and atmospheric circulation were carried out in some glaciarized regions, such as Arctic, North Pacific and Atlantic [2-7]. For Siberian glaciers such studies are still lacking [8, 9]. In this study we assessed the relationship between summer processes of regional atmospheric circulation (in lower and middle troposphere) and glacier ablation in southeast Siberia ridges over the period of 2001−13. We analyzed a set of regional synoptic whether maps and identified combinations of atmospheric pressure field characteristics associated with high and low glacier ablation (melting). We studied three glaciarized mountain ridges located in south-eastern Siberia: the East Sayan Range, the Baikalsky ridge and the Kodar Range (figure 1). The East Sayan extends from north-west to south-east over ~ 700 km (the highest peak is Munku-Sardyk, 3491 m a.s.l.). The Baikalsky is submeridional ridge extending along...
the western coast of Lake Baikal (the highest peak is Chersky Mountain, 2588 m). The Kodar is the northern sublatitudinal ridge (the highest peak is Bam, 3072 m a.s.l.), bordered by the Vitim and Olyokma tributaries of the Lena River.

![Image](image_url)

Figure 1. Studied glaciarized mountain ridges (East Sayan, Baikalsky and Kodar). SRTM model is used as a background. Upper left inset shows location of the studied region in Asia.

2. Material and methods
We used daily synoptic maps (for mean sea level, 850, 700, and 500 hPa) of the Irkutsk Center for Hydrometeorology and Environmental Monitoring for June–August 2001–13 to perform synoptic analysis of the regional atmospheric circulation patterns over our study area. The map data included such information as mean sea level pressure field, baric-topography maps (for levels 850, 700, and 500 hPa), air masses, atmospheric fronts, cyclones, anticyclones, and other forms of baric topography. The vertical extents of cyclones and anticyclones were estimated from the 500 hPa height field which corresponds to the middle troposphere level (about 5.6 km). The 700 hPa geopotential height (about 3 km a.s.l.) is close to the glacial zones of the study ridges and leading atmospheric air flows, as well as main pressure patterns were identified mainly based on this level. The atmospheric fronts, different types of advection, and the presence of moist air masses were determined on the weather maps of 850 hPa geopotential height.

Due to lack of mass-balance measurements on the glaciers in the study area we used the sum of positive temperatures (SPT) as a proxy of potential glacier ablation (melting) rate [10]. Daily temperatures over the period of 2001–13 were calculated between two atmospheric levels (700 and 850 hPa) using previously estimated lapse rates. We used the daily NCEP/NCAR reanalysis data as temperature and geopotential height records [11]. The SPT during the period of 2001–13 were calculated for mean elevation of glacier population for each ridge (see below).
3. Results

3.1. Sum of positive temperatures.
Statistical characteristics of the sum of positive temperatures (SPT) calculated in three studied glaciarized regions for the period 2001−13 are shown in table 1. The SPT show negative trend during the study period in all three regions with the trend for the Baikalsky Range is more pronounced (statistically significant). The lowest mean SPT is for Kodar Range and the highest on the Baikalsky Range, mainly, due to both mean glacier elevations (glaciers of the Baikalsky Range are the lowest) and with their latitude (glaciers of Kodar Range are the most northern). The mean duration of the SPT period ranges from 99 (Kodar) to 126 days (Eastern Sayan). Using the SPT thresholds we identified (based on deviations of the SPT values from the mean) years with maximal (SPT > [mean + st. dev.]), minimal (SPT < [mean − st. dev.]) and moderate ([mean − st. dev.] < SPT < [mean + st. dev.]) values of the SPT. For all three regions the years of 2001 and 2002 were characterized by the highest SPT. Abnormally low SPT observed in 2013 for the Eastern Sayan and the Baikalsky ranges and in 2003-2004 for the Kodar.

Table 1. Sum of positive temperatures (SPT) calculated for mean glacier elevations of three glaciarized regions for the period of 2001−13. Significant linear trend value (p<0.05) is in bold.

| Parameter                     | East Sayan | Baykalsky | Kodar |
|-------------------------------|------------|-----------|-------|
| Mean glacier elevation (m)    | 2260       | 1960      | 2240  |
| Mean latitude (°)             | 53.3       | 55.1      | 56.9  |
| Linear trend (°)              | −176       | −218      | −35   |
| Mean SPT (°C)                 | 857        | 926       | 663   |
| Standard deviation of SPT (°C)| 103        | 103       | 78    |
| Max threshold (°C)            | 960        | 1030      | 740   |
| Min threshold (°C)            | 754        | 823       | 585   |
| Mean duration of SPT period (days) | 126    | 123       | 99    |
| Years with maximal SPT        | 2001, 2002, 2007 | 2001, 2002 | 2001, 2002 |
| Years with minimal SPT        | 2009, 2013 | 2013      | 2003, 2004 |
| Years with moderate SPT       | 2003−06, 2008, 2010−12 | 2003−12    | 2005−13 |

3.2. Summer pressure fields
During the summer months the cyclonic (30-34% of the SPT period), anticyclonic (20-28%) and low gradient (24-27%) pressure fields were prevailing over the three glaciarized regions (figure 2). Passing of cyclones over the study area with sharply continental climate, as a rule, contributed to reduce the air temperature. By increasing the influence of cyclonic pressure field the sum of positive temperature are reduced. Analysis of baric topography maps showed that the cyclones moved mainly from south-west, north-west, west and south and anticyclones from the north-west, north-east and south-west. High cyclones (i.e. visible on the 500 hPa surface) accounted for 20% of the total, and contributed significantly to the air temperature decreases and hence, a reduction in the snow/ice melting. Positive air temperature anomalies with cloudless weather conditions occurred in anticyclonic pressure field facilitated the increased ablation. Sum of positive temperature increased with increasing the period of anticyclonic type of pressure field (figure 2). In 95% of cases, the anticyclones were secondary (or local), with period of 1-2 days, whereas high slow-moving anticyclones accounted for no more than 5% of cases.

The SPT increased with increasing the period of anticyclonic pressure field influence (figure 2). In 2001−02 anticyclonic pressure was prevailing over all studied regions. Another maximum of anticyclonic pressure field activity occurred over the East Sayan in 2007. The largest number of days
with cyclones (227) was observed over the Kodar. Enhanced cyclonic activity over the three regions was observed in 2003. Cyclonic pressure field patterns (with maximum in 2011–13) were dominated over the study period. Low gradient pressure pattern (25% of cases) is associated with a moderate glacier ablation summers. In general, the peaks of the SPT coincide with an increase in anticyclone and anticyclonic pressure field patterns, while the minimal SPT observed in summers with enhanced cyclone and cyclonic pressure field patterns.

![Figure 2](image2.png)

**Figure 2.** Frequency distribution (in days) of atmospheric pressure patterns over the East Sayan (a), Baikalsky (b) and Kodar (c) ridges during summer (June-August) periods of 2001–13. CPF is cyclonic pressure field, APF is anticyclonic pressure field and LGPF is low gradient pressure field.

Frontal activity occurred over the three study ridges both in low and high pressure fields. Warm atmospheric fronts were the most frequent and peaked in 2002 when the sum of positive temperature was the highest. Occluded fronts (complex fronts as a combination of warm and cold fronts) were more unusual. The largest amount of cold fronts with usual development of convective clouds and heavy rainfall moved over the Eastern Sayan and Baikalsky ridges in 2013. Maximal number of cold fronts over the Kodar Range was recorded in 2011. During the summer months the mid-latitudes continental air (relatively warm and humid) was dominated over the study area. The number of days with heat and cold advection are almost equal, but their temporal distribution is non-uniform. In 2002 the heat air advection occurred in about 80% of cases (days), while in 2013 the cold air advection was prevailing.

### 3.3. Relationship between the SPT and atmospheric circulation

The correlation coefficients between the sum of positive temperature and regional atmospheric circulation characteristics are presented in table 2. There are the links between the SPT and almost all types of pressure fields and atmospheric fronts. We found significant positive correlations between the SPT and anticyclonic fields, warm atmospheric fronts and warm air advections. A significant negative correlation was found between the SPT and cyclonic activity and cold air advections. The highest correlation coefficients were observed over the Baikalsky Range and the Eastern Sayan. The anticyclonic pressure fields, warm atmospheric fronts and heat air advections were associated with
increased SPT and snow/ice ablation, whereas cyclones and cold air advections contributed to lower SPT and ablation. The SPT (and ice melting) on the Kodar increased significantly under influence of anticyclonic pressure field and warm and occluded atmospheric fronts, and decreased when passing the cyclones through the ridge.

**Table 2.** Correlation coefficients between the sum of positive temperatures calculated for mean elevation of glaciated zone of three ridges and frequency of some atmospheric circulation patterns. Significant values (p < 0.05) are in bold.

| Atmospheric parameter (unit)                  | East Sayan | Baikalsky | Kodar  |
|----------------------------------------------|------------|-----------|--------|
| Cyclones (days)                              | –0.24      | –0.44     | –0.78  |
| Cyclones (count)                             | –0.49      | –0.63     | –0.60  |
| Cyclonic pressure field (days)               | –0.54      | –0.20     | 0.23   |
| Anticyclones (days)                          | 0.22       | 0.19      | –0.01  |
| Anticyclones (count)                         | 0.31       | 0.12      | 0.02   |
| Anticyclonic pressure field (days)           | 0.56       | 0.88      | 0.70   |
| Low gradient pressure field (days)           | 0.13       | –0.28     | –0.03  |
| Cold fronts (days)                           | –0.10      | 0.10      | 0.28   |
| Occluded fronts (days)                       | 0.32       | 0.18      | 0.52   |
| Warm fronts (days)                           | 0.60       | 0.74      | 0.46   |
| Cold air advections (days)                   | –0.65      | –0.73     | –0.15  |
| Heat air advections (days)                   | 0.65       | 0.73      | 0.15   |
| Warm and moist air masses (days)             | –0.16      | –0.17     | –0.16  |

**4. Discussion**

Previously we found that the area of southeast Siberia glaciers had decreased by ~59% between 1850 and 2011 corresponding to a significant positive temperature trend at least over the past 130 years [12, 13]. The period of 2001–05 was the warmest in the instrumental temperature record (since 1882) that contributed to increased glacier melting. However, during the second part of the first 21st century decade temperatures decreased across the study region. The most intensive area shrinkage of glaciers occurred between 2001 and 2011, probably, due to delayed response of glaciers to temperature increase from mid-1970s to mid-2000s (by ~2.5 °C). The results of this study suggest that the positive temperature anomaly recorded in 2001–2002 across the region occurred due to the peculiarities of summer atmospheric circulation, such as anticyclonic pressure field influence (cloudless weathers), warm front activity with warm air advections. A similar link between summer ablation and macro-circulation mechanisms in the atmosphere has been established from mass balance studies of glaciers in North-East Siberia [14]. The authors concluded that the positive anomalies of summer temperature (in the background anticyclonic type of pressure field) were caused by mainland (non-Arctic) anticyclone or low gradient pressure field.

The largest ice area reduction since ~1995 has occurred on Kodar glaciers [15, 16]. Probably this is due to high sensitivity of the glaciers both to climate change and to local topography influence. Also it was found that enhanced melting of Kodar glaciers often correlates with such atmospheric circulation patterns as lower pressure under influence of warm and humid air mass, and heat air advection at the altitudes of 2.5-3.0 km [12]. More moderate ice reduction the Baikalsky Range glaciers compared with the other two ranges is probably due to: 1) specific climate in the Lake Baikal surrounding, which is characterized by higher winter temperatures and lower summer ones; 2) enhanced influence of
secondary Lake Baikal cyclones formed under the influence of mountain terrain and bringing significant portions of snowfall to the glaciers.

The geographic location of the glaciarized mountain ridges can also affect the circulation. East Sayan Range is an orographic barrier for cyclones to move from west to east. Some part of precipitation from western and southern cyclones falls in this area, while a significant number of cyclones, rounding the East Sayan move to the north-east of the study area (Baikalsky and Kodar ridges). Probably, ice melting on the East Sayan is reduced by frequent early summer snowfalls from southern and western cyclones. The predominance of air transformation processes in a low pressure field is mostly associated with the air masses of warm cyclone sector (mid-latitude continental or tropical air).

Decreasing SPT trends in 2001–13 suggest that summer ablation tends to decrease and glacier mass balance will gradually recover. During the same period (2001-2013) the SPT in the high-mountain zone (~3000 m a.s.l.) of the East Sayan ridge demonstrated a negative trend [9]. Shortening of duration of elementary atmospheric circulation mechanisms unfavorable for glacier mass-balance during the last decade was revealed in the North-East Siberia [14]. The authors also found a decrease in air temperature associated with either cyclonic activity (cold air advections, cloudiness, precipitation and heat losses through evaporation) or advections of cold arctic air. [17] revealed a similar negative trend in ablation on the Djankuat Glacier in Caucasus Mountains after 2000.

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