Synoptic processes over the Kodar glacier zone during the ablation period

O P Osipova¹ and E Y Osipov²

¹Sochava Institute of Geography of SB RAS, Irkutsk, Russia
²Limnological Institute of SB RAS, Irkutsk, Russia

E-mail: olga@irigs.irk.ru, eduard@lin.irk.ru

Abstract. The small glaciers of the Kodar ridge (south of Eastern Siberia), located inland Asia under the influence of both Atlantic and Pacific air transport, are the valuable objects for studying their response to changes in mid-latitude atmospheric circulation. However, detailed meteorological studies on the glaciers have been limited so far. For the first time, in July–August 2019, the meteorological characteristics were measured on the Sygyktinsky glacier using automatic weather station. We have analyzed the relationship between variations of large-scale atmospheric circulation and meteorological regime of the glacier using the NCEP–NCAR reanalysis data. During the observation period, Kodar was under the influence of a positive geopotential anomaly in the lower troposphere, which determined increased temperatures and decreased relative humidity and precipitation. Quasi-cyclic fluctuations in meteorological time series (e.g. air temperature) reflect the influence of large scale synoptic changes caused by the front passages, warm and cold air advections. High ablation rates on the glacier were associated with anticyclones, subtropical ridges, and warm air advections (from southeast and southwest), while decreased ablation was observed during the cyclone passage and cold air advection (from north, northeast, and west).

1. Introduction
Over the past decades, global warming has led to a widespread shrinkage of the cryosphere with the mass loss of ice sheets and glaciers [1]. The mass balance of mountain glaciers is very sensitive to changes in atmospheric circulation; therefore, climate research in high mountain areas is of particular scientific interest. However, the observation network in the mountains is very sparse, leading to significant uncertainties of climate models and their reanalyses. Often, sparse observation network in remote mountain areas does not allow to catch the changes in middle to large scale atmospheric circulation. The use of automatic weather stations installed directly on glaciers helps to fill these data gaps. High resolution in situ measurements of meteorological variables contribute to better understanding of physical processes linking atmospheric and cryospheric changes.

Small mountain glaciers of south Eastern Siberia are located in remote areas (inner parts of Asia) and concentrated mainly on Eastern Sayan, Baikalsky and Kodar ridges. Explorations based on satellite imagery mapping showed that the glaciers have been actively reducing both in area and in thickness since the Little Ice Age termination [2]. The Kodar glaciers have decreased in area the most, by about 60% [2] with the accelerated shrinkage rate recorded for late twentieth century [3, 4]. At present, there are about forty Kodar glaciers distributed within the altitude range from 1900 to 2800 m a.s.l. and influenced by both Atlantic and Pacific moisture-bearing air masses [5, 6]. The glaciers have
been explored since the mid-20th century [5, 7], but no long-term mass balance and meteorological measurements on them have not been conducted until recently. Inland location of the Kodar ridge (the highest peak Bam is 3072 m above sea level), under the influence of both Atlantic and Pacific air transport, makes this area important for studying the response of glaciers to changes in large-scale mid-latitude atmospheric circulation.

In summer of 2019, we installed the automatic weather station on the Sygyktinsky glacier, Kodar ridge (figure 1), and measured meteorological parameters at the atmosphere/glacier boundary during the melt season. In this study, we investigate the relationship between some meteorological variables from glacial zone and large-scale atmospheric circulation processes in lower troposphere. The main focus was on the effect of atmospheric circulation on the rate of surface glacier melting.

![Figure 1. Location of the Kodar Ridge on the Asian continent.](image)

2. Models and methods
The automatic weather station was installed in early July 2019 on the Sygyktinsky glacier (56° 51.02' N, 117° 25.09' E, 2561 m a.s.l.). A complex of meteorological parameters, including air temperature, relative humidity (both at 2 m above the surface), atmospheric pressure, precipitation, shortwave and longwave radiation fluxes was recorded with a 30 min frequency. All sensors were synchronized (time zone +8 GMT). Here we present and discuss the daily averaged meteorological dataset for the July–August period focusing on temperature variations as possible predictors of ablation.

Daily variations of large scale atmospheric circulation throughout the study period were analysed using the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis data [8]. We analysed the fields of 1000, 700 and 500 hPa geopotential heights and their anomalies (1981-2010 climatology). The 700 hPa level corresponds to high peaks of the Kodar ridge and therefore well suited for describing atmospheric processes and winds over the glacial zone, while the 500 hPa level describes the atmospheric changes in lower troposphere. Composite maps were built for each day of the study period using online tool of the Earth System Research Laboratories (ESRL, https://www.esrl.noaa.gov). All daily baric fields at 700 hPa were classified and assigned to high and low ablation days. In addition, we used data on cloud cover from the Chara weather station, as the closest to the glacier.

3. Results and discussion

3.1. Pressure field
In July-August 2019, the study area, with an average sea level pressure of 1008 hPa, was located on the north-eastern periphery of large low-pressure system originated from tropical latitudes. Low-
pressure systems were dominated at mean sea level. The frequency of cyclones, low-gradient and anticyclonic fields was 35%, 53%, and 12%, respectively. In the lower troposphere near the glacial zone (700 hPa) the anticyclonic field prevailed (60%) over the cyclonic one (40%). While the sea level pressure field was close to the long-term average, a positive anomaly was observed in lower and middle troposphere, from +25 gpm at 700 hPa to +35 gpm at 500 hPa. The centre of this anomaly within the Asian continent was located above the Taymyr Peninsula (+85 gpm at 500 hPa) (figure 2).

The features of the low troposphere baric field caused the anomalous weather conditions over the Kodar throughout the summer period, in particular increased air temperature, decreased relative humidity and precipitation intensity. During July-August 2019 the air temperature anomaly at 700 hPa was +1.5 °C from the 1981–2010 average and there was a deficit of precipitation, with an anomaly in precipitation intensity of −0.6 mm day⁻¹.

3.2. Glacier meteorology
The daily average values of meteorological variables in the glacial zone are shown in figure 3. Air temperature varied from −0.2°C to 12.8°C, and relative air humidity from 41 to 100%. During the observation period, 136 mm (in water) of precipitation fell onto the glacier (53 mm in July, 83 mm in August). The atmospheric pressure varied from 743 to 757 hPa. Day-to-day changes in atmospheric pressure are generally associated with the passage and stationing of high and low pressure systems over the region. The predominance of cyclonic circulation over the study area resulted in increased cloud cover (Chara weather station data), especially of middle and low levels. In July–August, the total cloud cover was 66%, while cloudiness of low level 41%. The state of lower cloudiness strongly correlated with air temperature; clear sky days (average temperature 9.8°C) were warmer than the overcast ones (2.8°C).

3.3. Weather conditions and ablation during temperature extremes
Air temperature shows quasi-cyclic fluctuations, expressed as positive and negative anomalies. During the study period five warm/cold waves caused by variations of synoptic patterns were observed (figure 3). The mean duration of the waves (from 2 to 5 days) is comparable to the elementary synoptic periods, during which the type of the baric field and air mass properties are preserved. These changes, in particular, were due to atmospheric front passage and warm (from west, southwest and southeast) and cold (from north, northeast and northwest) air advections. Mostly, positive anomalies were associated with anticyclones and ridges (55% days at 700 hPa), while negative with cyclones (16% at 700 hPa).
Figure 3. Some meteorological parameters (daily average values) measured on the glacier from 07/07/2019 to 24/08/2019 with automatic weather station.

Changing synoptic patterns led to changes in weather conditions in the glacial zone. Deviations of meteorological variables from the study period mean for positive and negative air temperature extremes are indicated in Table 1.

Table 1. Deviations of meteorological parameters (from the mean for the period from 07/07/2019 to 24/08/2019) during temperature extremes.

| Period   | $T_{\text{mean}}$ | $P$ | $C_{\text{total}}$ | $C_{\text{low}}$ | $RH$ | $S_{\text{in}}$ | $S_{\text{net}}$ | $L_{\text{in}}$/$L_{\text{net}}$ | $R_{\text{net}}$ | Ablation |
|----------|------------------|-----|-------------------|-----------------|------|----------------|----------------|------------------------|----------------|----------|
|          | °C               | hPa | %                 | %               | %    | W m$^{-2}$    | W m$^{-2}$    |                       | W m$^{-2}$ | mm       |
| Positive extremes: |         |     |                   |                 |      |               |               |                       |               |          |
| 7.07     | 5.4             | 1.8 | 3                 | -22             | -31  | 112           | 2             | -8                     | -7             | 38        |
| 10–12.07 | 2.1             | 3.0 | -5                | 0               | 0    | -2            | -41           | 0                      | -41            | -5        |
| 17–18.07 | 4.9             | 1.4 | -17               | -5              | -6   | 86            | 10            | 6                      | 15             | 5         |
| 25–29.07 | 4.5             | -4.7| -16               | -19             | -22  | 78            | 47            | -16                    | 30             | 13        |
| 7–9.08   | 4.9             | 6.0 | -45               | -39             | -34  | 67            | 90            | -30                    | 59             | 7         |
| Mean     | 4.4             | 1.5 | -16               | -17             | -18  | 68            | 22            | -10                    | 11             | 11        |
| Negative extremes: |       |     |                   |                 |      |               |               |                       |               |          |
| 9.07     | -2.0            | -1.0| 29                | 27              | 23   | -119          | -80           | 37                     | -44            | -13       |
| 14.07    | -3.4            | -2.0| 32                | 29              | 21   | -59           | -63           | 34                     | -30            | -6        |
| 20.07    | -3.1            | -1.5| 27                | 21              | 21   | -53           | -50           | 17                     | -34            | -4        |
| 4–5.08   | -4.8            | 1.7 | 8                 | 3               | 12   | -32           | 2             | -21                    | -19            | 0         |
| 13–21.08 | -5.4            | -2.4| 16                | 25              | 22   | -87           | -40           | 24                     | -16            | -16       |
| Mean     | -3.7            | -1.0| 22                | 21              | 20   | -70           | -46           | 18                     | -29            | -8        |

* $T_{\text{mean}}$ is mean daily air temperature, $P$ is atmospheric pressure, $C_{\text{total}}$ is total cloudiness (according to data from Chara station), $C_{\text{low}}$ is lower cloudiness (according to data from Chara station), $RH$ is relative humidity, $S_{\text{in}}$ is incoming shortwave radiation, $S_{\text{net}}$ is net shortwave radiation, $L_{\text{in}}$ is incoming longwave radiation, $L_{\text{net}}$ is net longwave radiation, $R_{\text{net}}$ is net radiation.

Characteristic weather conditions during positive extremes were almost complete absence of lower cloud cover (clear or semi-clear sky), lower relative air humidity, increased atmospheric pressure, incoming shortwave radiation, net shortwave radiation, net longwave radiation, net radiation and ablation. On the days of temperature minima, the sign of the deviations changed to the opposite.
A comprehensive analysis of the circulation mechanisms, temperature regime and cloudiness made it possible to identify synoptic conditions under which the increased and decreased glacier melting occurs. The high surface ablation of the glacier were associated with anticyclones or ridges at 700 hPa (figure 4a), while smaller with cyclonic field, when the study area was in cyclone area or at its periphery (figure 4b). It is obvious that the ablation rate on the Sygyktinsky glacier is strongly controlled by the surface energy balance which is mainly determined by net shortwave radiation (table 1). This parameter, in turn, is broadly controlled by cloud cover (especially, of low level) and albedo. The higher melting rates under clear-sky conditions found on the Kodar glacier are consistent with a similar relationship in the European Alps [9]. A decreased ice melting under cyclonic weather conditions is due to increased lower cloud cover and reduced shortwave radiation coming to the glacier surface. On the other hand, under anticyclonic influence an increase of net shortwave radiation results in increased melting rate. Another important factor influencing the ablation was the albedo of glacier surface [10]. Over the summer period, albedo on the Sygyktinsky glacier greatly changed during the snowfall days (in August), with the net radiation decreased by more than 2 times. Summer snowfalls were mainly due to the passage of cyclones and advection of cold air from the Arctic region. Thus, cyclonic activity over the study area contributed to a decrease in glacier ablation both through an increase in cloudiness and in albedo.

Figure 4. Composite maps of 700 hPa geopotential height (m) on 7 August 2019 (a) and 20 July 2019 (b). The star shows the location of the research area.

4. Conclusion

Atmospheric circulation over the Kodar ridge is formed under the influence of its inland geographic position, alpine relief, and multidirectional air mass flows. The positive anomaly of geopotential height in low troposphere (at 700 and 500 hPa levels) during the summer period of 2019 resulted in slightly abnormal weather conditions, with positive anomaly for air temperature and negative for precipitation over the study area. Meteorological variations in the glacial zone (Sygyktinsky glacier) throughout the ablation period broadly reflect the influence of large scale synoptic changes caused by the front passages, warm and cold air advections. Increased melt of the glacier occurred under conditions of stationary continental anticyclone and subtropical ridge, and warm air advection (from southeast and southwest). Decreased ablation was observed during invasions of Arctic air, stationing of western and southwestern cyclones and cold air advection (from north, northeast, and northwest). The link between the meteorological regime of the glacier, its ablation and large scale atmospheric circulation patterns is clearly manifested through the weather conditions, and their classification is an important task of further glacioclimatic studies of the Kodar glaciers.
Acknowledgement
The study was supported by the Russian Foundation for Basic Research (grant 19-05-00668) and by the Programs No. 0345-2019-0006 (AAAA-A16-116122110063-0) and No. AAAA-A17-117041910172-4.

References
[1] IPCC 2014 Climate Change: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (Geneva: IPCC Publishing) p 151
[2] Osipov E Y and Osipova O P 2014 Mountain glaciers of southeast Siberia: current state and changes since the Little Ice Age Ann. Glaciol. 55(66) 167-76
[3] Shahgedanova M, Popovnin V, Aleynikov A and Stokes C R 2011 Geodetic mass balance of Azarova glacier, Kodar Mountains, eastern Siberia, and its links to observed and projected climatic change Ann. Glaciol. 52(58) 129-37
[4] Stokes C, Shahgedanova M, Evans I and Popovnin V 2013 Accelerated loss of alpine glaciers in the Kodar Mountains, south-eastern Siberia Global Planet Change 101 82-96
[5] Preobrazhenskiy V S 1960 Kodar Glacial Area (Moscow: Publishing House of the Academy of Sciences of the USSR) p 73
[6] Krenke A N 1982 Mass-Exchange in Glacier Systems over the Territory of the USSR (Leningrad: Gidrometeoizdat) p 288
[7] Novikova Z S and Grinberg AM 1972 Catalogue of Glaciers of the USSR, Lena-Indigirka Region, Basins of Chara and Vitim Rivers, Kodar Ridge (Leningrad: Gidrometeoizdat) p 43
[8] Kalnay E et al 1996 The NCEP/NCAR 40-Year Reanalysis Project Bull. Am. Meteor. Soc. 77 437-71
[9] Pellicciotti F, Brock B, Strasser U, Burlando P, Funk M and Corripio J 2005 An enhanced temperature-index glacier melt model including the shortwave radiation balance: Development and testing for Haut Glacier d’Arolla, Switzerland J Glaciol. 51(175) 573-87
[10] Oerlemans J and Klok E 2004 Effect of summer snowfall on glacier mass balance Ann. Glaciol. 38 97-100