Meteorological regime of the glacier No. 18 (the Peak Topografov massiv, East Sayan range)

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Abstract. For the first time, experimental data on the meteorological regime of a continental glacier (No. 18, East Sayan range, south of East Siberia) have been obtained during the summer seasons of 2015–2017. Standard meteorological parameters, such as air temperature, humidity, atmospheric pressure, precipitation, incoming short-wave solar radiation, wind speed, and wind direction were measured by using the automatic weather station installed at the lower part of the accumulation area of the glacier (at elevation 2,550 m). It was established that the meteorological regime of the glacier is characterized by a relatively high mean daily temperatures, humidity and cloudiness, while mean wind speed is relatively low. Liquid precipitation dominates over the solid one and condensation over evaporation. It has been found that temperature and precipitation time series on the glacier correlate well with those at the nearest weather station Orlik and NCEP/NCAR reanalysis data. The main energy sources for snow/ice melting have been estimated and the main contribution to glacier ablation has been attributed to net shortwave radiation.

1. Introduction
The problem of climate change of global and regional scales is of great importance. Over the past decades, climatic characteristics have undergone significant fluctuations with global warming trend [1]. Therefore, there is a need to assess the direction of climatic trends in individual regions of the globe. The climate of mountain glaciarized areas has a great scientific and practical interest in this sense. Glaciers are the most important components of the water balance and one of the most sensitive indicators of climate change. Mountain glaciers are usually located in remote areas where there are few or no weather stations. In such cases, climate fluctuations can be estimated by the current regime of these glaciers, which is determined by the climatic conditions of the accumulation and ablation seasons.

Comparison of multitemporal inventories of the glaciers in the south of East Siberia showed that their area has decreased by almost 60% since the Little Ice Age with the accelerated ice shrinkage occurred at the end of the 20th century [2, 3]. However, the mechanisms of interaction between mass balance of the glaciers and atmosphere processes are still unclear in detail. To overcome this shortcoming, the direct studies of local climate on glaciers are required. In recent decades, automatic meteorological stations installed directly on glaciers are often used for the detailed study of the interaction between glaciers and climate. The number of such glaciers in different geographic areas is increasing from year to year. However, it should be noted that meteorological regime of continental Siberian glaciers almost was not investigated by using such approach. The main purpose of this study...
was to investigate the meteorological regime and physical processes controlling ice/snow melt on a continental East Sayan glacier.

2. Study glacier and meteorological observations

The East Sayan (the highest peak is Munku-Sardyk; 3,492 m a.s.l.) is a mountain range in southern Siberia, near the border between Russia and Mongolia. Meteorological measurements were conducted on the valley glacier No. 18 [4]. Recently we completed the latest inventorying of the East Sayan glaciers and evaluated their changes since the Little Ice Age [3]. The study glacier is located in upper reaches of the Helgin River, on the Peak Topografov massif (3,015 m a.s.l.). This is the second largest (0.93 km²) and the longest (2.01 km²) glacier in the East Sayan range. The glacier is in altitude range from 2,320 to 2,950 m and it has a north-eastern aspect. The late summer firn line is about 2,500 m a.s.l., the average slope of ice surface is 17°.

We used a low-cost automatic weather station (AWS) (Davis Vantage Pro2) measuring such parameters as air temperature, humidity, precipitation, atmospheric pressure, shortwave radiation, wind direction and speed. In August 2015 the AWS was installed on small supraglacial moraine in lower part of accumulation area at elevation 2,550 m. In the summers of 2016 and 2017 it was re-installed at the same place. The sensors were located at 2 m level above the ground surface. The measured data archived for every 1 hour.

3. Results and discussion

3.1. Meteorological characteristics

Measured meteorological characteristics for three summer periods are summarized in the table 1. The mean air temperature was relatively high (from +8 to +11°C). The maximum temperature reached

Table 1. Averaged meteorological characteristics measured at the glacier No. 18 during the observation periods of 2015–2017.

| Parameter                        | 17-27 Aug 2015 | 29 Jun – 25 Aug 2016 | 22 Jun – 24 Aug 2017 |
|----------------------------------|----------------|-----------------------|-----------------------|
|                                 | Min | Max | Mean | Min | Max | Mean | Min | Max | Mean |
| Air temperature (°C)             | -1.5 | 18.9 | 10.8 | -3.0 | 19.8 | 8.0 | -3.3 | 18.9 | 7.5 |
| Relative humidity (%)            | 28 | 95 | 56 | 37 | 97 | 84 | 27 | 96 | 76 |
| Vapour pressure (hPa)            | 5.0 | 11.2 | 6.9 | 4.8 | 14.7 | 9.0 | 4.6 | 11.4 | 8.0 |
| Specific air humidity (g kg⁻¹)   | 4.1 | 9.3 | 5.7 | 3.9 | 12.3 | 7.4 | 3.8 | 9.7 | 6.6 |
| Wind speed (m s⁻¹)               | 0.0 | 7.2 | 1.9 | 0.4 | 13.9 | 3.2 | 0.0 | 7.6 | 2.0 |
| Atmospheric pressure (hPa)       | 745.6 | 768.5 | 755.6 | 741.0 | 777.5 | 757.8 | 739.1 | 762.7 | 752.0 |
| Mean sea level atmospheric pressure (hPa) | 1000.6 | 1023.5 | 1010.6 | 991.0 | 1027.5 | 1007.8 | 994.1 | 1024.9 | 1007.8 |
| Total precipitation (mm w.e.)    | 2.8 | ≥342.6 | ≥348.2 |
| Solid precipitation (mm w.e.)    | 0.0 | ≥23.8 | ≥11.8 |
| Cloud cover (%)                  | 0 | 100 | 37 | 0 | 100 | 76 | 0 | 100 | 64 |
| Shortwave radiation (W m⁻²)      | 0 | 885 | 188 | 0 | 989 | 186 | 0 | 993 | 163 |
| Daily shortwave radiation (cal cm⁻²) | 303 | 488 | 396 | 122 | 706 | 377 | 68 | 670 | 330 |

* at Orlik station
+20°C, the minimum temperature was −3°C. However, the negative mean daily temperatures were observed only for 3 days in August 2016. The relative humidity was also high (mean values of 56-84%) and varied in the range from 28 to 97%. The wind speed at some moments reached 14 m s\(^{-1}\), but its mean values did not exceed 3 m s\(^{-1}\). Precipitation almost always fell in liquid form, except for 6 days in the middle and end of August 2016. The proportion of solid precipitation did not exceed 10%. Cloud cover varied from 0 to 100% with mean value of 37–76%. There were only one day with 100% cloud cover during the observation period in 2015, and 9 days in 2016. The incoming short-wave radiation reached 1000 W m\(^{-2}\), with the daily mean values of 190 W m\(^{-2}\).

The daily cycles of the meteorological parameters are shown in the figure 1. The air temperature reached maximum between 15:00 and 17:00, and the minimum between 5:00 and 7:00. Relative humidity shows strong negative correlation with temperature (r=-0.98), with the highest values in night and morning hours (maximum between 7:00 and 8:00), and the lowest in the daytime hours (minimum between 15:00 and 16:00). The wind speed reaches the maximum values in the daytime (between 13:00 and 15:00) with following decreasing. Atmospheric pressure was characterized by two maxima (night and day) and two minima (morning and evening). The night maximum (00:00–01:00) and morning minimum (05:00–06:00) were most clear. Precipitation and cloud cover did not show a clear daily cycle, but slightly more precipitation falls in the evening and night hours (22:00–23:00). Cloud cover tends to increase by evening. The total shortwave radiation had positive values between 7:00 and 20:00 with a maximum between 14:00 and 15:00. That is the duration of the daylight period was about 13 hours. The daily variations of shortwave radiation strongly correlated with air temperature (correlation coefficients are 0.62–0.67) and relative humidity (correlation coefficients are from -0.65 to -0.69). However, the maximum of air temperature showed two hours lag compared with shortwave radiation.

![Figure 1](image.png)

**Figure 1.** Averaged diurnal cycles of meteorological parameters at the glacier during the observation periods of 2015–2017. The captions above the curves indicate the time of maximum and minimum values.

### 3.2. Heat fluxes near glacier surface

Diurnal variations of radiation fluxes are shown in the figure 2. Shortwave radiation was measured directly by the AWS. Longwave radiation was calculated from air and glacier surface temperatures based on the Stefan-Boltzmann law [6]. In contrast to the longwave fluxes, shortwave radiation varied
greatly during the day. The maximum of incoming and reflected shortwave radiation was observed between 13:00 and 15:00. The incoming longwave radiation varied little after air temperature and had maximum value between 16:00 and 18:00, and minimum between 06:00 and 07:00. As we adopted the mean daily surface temperature equal to zero, the outgoing long-wave radiation was constant. At night time (20:00–10:00) the net radiation (balance between incoming and outgoing shortwave and longwave radiation) was negative.

Figure 2. Diurnal cycles of radiation fluxes near the glacier surface during the observation periods of 2015–2017. S is shortwave radiation (incoming↓ and outgoing↑), and L is longwave radiation (incoming↓ and outgoing↑), and $R_n$ is net radiation.

3.3. Contribution of energy balance components to snow/ice melting

Such components as sensible and latent heat fluxes, heat fluxes by rain and thermal conductivity were calculated by using the published formulas [7, 8]. In order to calculate turbulent heat fluxes we used the bulk aerodynamic method. Non-dimensional stability functions were calculated using Richardson number, an indicator of atmospheric stability and its positive values indicate a stable stratification in atmosphere.

In absolute terms, net shortwave radiation was approximately two times greater than net longwave radiation (mean values were 95 and $-51$ W m$^{-2}$, respectively). Sensible and condensation heat prevail in fluxes towards the glacial surface, with sensible heat slightly exceeded the latent one. Maximum values of sensible and latent fluxes reached 100 W m$^{-2}$, and the minimum was $-10$ W m$^{-2}$ (mean values were about $+10$ W m$^{-2}$). Heat loss by the subsurface thermal conductivity was constant and
very insignificant (~0.4 W m$^{-2}$). The heat arrival with rain was also minor on average (about 2 W m$^{-2}$) but on some days it reached 16 W m$^{-2}$. The daily fluctuations of heat corresponded to melting or freezing were significant (from ~47 on August 11 to 207 W m$^{-2}$ on August 2) with mean value of 63 W m$^{-2}$. In 2015, freezing occurs only for one day (August 17), and in 2016 for 7 days (in 10, 11, 13, 16, 23–25 August).

The distribution of the surface energy balance components is summarized in the table 2. In the incoming part of the heat balance, the net shortwave radiation was prevailed (75–94%). The sensible heat accounted for 6–13%, and latent heat of condensation up to 10%. That is, the main source of melting heat was shortwave radiation. It was followed by turbulent transfer and a latent flux due to condensation. The main heat loss occurred as a result of net longwave radiation from the glacial surface amounting to 40–50%. The rest of the heat was spent for melting.

**Table 2.** The structure of surface energy budget of the glacier No. 18 during the observation periods of 2015–2017 (daily mean values). $S_n$ is net shortwave radiation, $L_n$ is net longwave radiation. $H$ is sensible heat flux, $LE$ is latent heat flux, $Q_r$ is sensible supplied by rain, $Q_s$ is conductive heat flux through the glacier subsurface, and $Q_m$ is melting energy.

| Observation period | Input | Output | Input | Output |
|--------------------|-------|--------|-------|--------|
|                    | $S_n$ | $H$    | $LE$  | $Q_r$  | $L_n$ | $Q_s$ | $Q_m$ | $S_n$ | $H$ | $LE$ | $Q_r$ | $L_n$ | $Q_s$ | $Q_m$ |
| 17–26 Aug 2015     | 96    | 6      | 0     | 0      | −50   | 0     | −53   | 94    | 6   | 0    | 0      | 49    | 0     | 51    |
| 29 Jun – 25 Aug 2016 | 94    | 17     | 13    | 2      | −53   | 0     | −73   | 75    | 13  | 10   | 2      | 42    | 0     | 58    |
| 22 Jun – 24 Aug 2017 | 81    | 9      | 7     | 2      | −58   | 0     | −40   | 82    | 9   | 7    | 2      | 59    | 0     | 41    |

4. Conclusion
Meteorological observations have been firstly carried out on the glacier No. 18 (continental south Siberia, East Sayan Range) to study the relationships between glacier melt and weather conditions during three summer seasons (2015–2017). Also we estimated the surface energy fluxes near the glacier surface and analyzed their variations.

The summer meteorological regime over the glacier was characterized by high mean air temperature (11°C), low wind speed (3 m s$^{-1}$), high relative humidity (84%) and cloud cover (76%). The condensation was predominated over evaporation. The air temperature and precipitation on the glacier was significantly correlated with the nearest weather station Orlik. The main energy source for melting was the net shortwave radiation (up to 95%). This value agrees well with the results of studies carried out on other Asian glaciers, for example, located in southeast Tibetan Plateau [9] and western Qilian mountains [10]. It also suggests that ice/snow albedo is a sensitive parameter affecting the surface energy balance. The second important source of heat was turbulent heat fluxes and it was strongly controlled by weather conditions. The sensible heat flux and latent heat (due to condensation) accounted for 13 and 10% of total melting heat, respectively. Turbulent fluxes were particularly larger on days with high ablation. The net longwave radiation was the principal energy sink (up to 50%) and the largest contributor to daily variability of surface energy balance. Further studies (with more advanced equipment) should focus on obtaining additional experimental (including spatially distributed) data on surface glacier temperature, mass balance, longwave radiation and turbulent heat fluxes.

Acknowledgements
The present study was supported by the Russian Foundation for Basic Research (grant 19-05-00668).
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