Summertime evaporation over two lakes in the Schirmacher Oasis, East Antarctica

Elena Shevnina[1], Timo Vihma[1], Miguel Potes[2] and Tuomas Naakka[1]

[1] Finnish Meteorological Institute, Helsinki, Finland
[2] Center for Sci-Tech Research in Earth System and Energy, Institute for Advanced Studies and Research, University of Évora, Évora, Portugal

Correspondence to: Elena Shevnina (elena.shevnina@fmi.fi)

Abstract. The study quantified uncertainties in mass-transfer formulas applied for estimations of summertime evaporation over two lakes in the Schirmacher Oasis, East Antarctica. The evaporation over the lakes was measured by the eddy-covariance (EC) technique during the austral summers (December – February) in 2017 – 2018 and 2019 – 2020. These direct measurements showed that summertime evaporation over two lakes varied from 0.3 to 5.0 mm d^{-1}. Depending on the ice cover presence, the average evaporation varied from 1.6 ± 0.1 mm d^{-1} in December to 3.0 ± 0.2 mm d^{-1} in January – February. In summer, the lakes were warmer than the ambient air, and the largest day-to-day variations in evaporation were associated with variations in the wind speed. The EC measurements were used as a reference for evaluating the uncertainties of the indirect methods. The bulk-aerodynamic method gave the most accurate estimates of evaporation over two lakes (of 6 – 8 %), and this method showed acceptable skill scores (by two selected criteria) in estimation of the daily evaporation during the lakes' ice breaking-up and open water periods. This method is recommended for hydrological (lake water balance) applications required for operational (short term) decision making. Other indirect methods (combination formulas) underestimated the summertime evaporation by 27 – 73 %.

1 Introduction

Antarctica shelters numerous water bodies containerizing meltwater in a complex hydrological system of lakes and streams. Every summer, approximately 60000 lakes are formed on the surface of the ice shelf and margins of the continental ice sheet. The largest surface lakes are found in East Antarctica, where the seasonal variations in lake surface area is the highest (Dirscherl et al., 2021), and in the Antarctic Peninsula (Stokes et al., 2020; Shen et al., 2025). These lakes speed-up calving of the marginal glaciers, which contributes to the global sea level rise and increases the risk of collapse of ice shelves due to hydro-fracturing (Rignot et al., 2004; Banwell et al., 2013; Arthur et al., 2022). Providing a moisture source to the atmosphere through evaporation, these surface lakes may also affect local weather by fostering fog formation.

There are approximately 115 permanent settlements in Antarctica, most of them located along the continental coast, in rock oases and sub-Antarctic islands (Antarctic station catalog, 2025). Since the COVID-pandemic, the number of people visiting Antarctica has increased by 40 %, and is expected to grow further by approximately 12.5 % per year (Bastmeijer et al., 2023). The nearest lakes often serve freshwater for the settlements, and evaluation of the lakes' water resources (water balance) is a crucial task for their managers (Kaup, 2004; Sokratova, 2011). Relying on short-term weather forecasts, the managers make operational decisions and expectations on lake water inflow/outflow. The decisions on maintenance of settlements and investments rely on seasonal and climate-scale perspectives (Lan et al., 2025). The Antarctic lakes house unique lifeforms (Rothschild and Mancinell, 2004; Andersen et al., 2011; Keskitalo et al., 2013). Understanding the hydrological regime and lakes' water balance is important to save these ecosystems (Faucher et al., 2019). It requires reliable hydrological observations on lakes, and methods allowing evaluation of components of the water (mass) balance equation.

The lake water balance equation describes changes in the lake volume depending on changes in the surface inflow, outflow runoff, precipitation and evaporation/sublimation over the lake surface area, artificial water withdrawal, underground inflow/outflow runoff. Contributions of some of the above-mentioned components to the total lake volume change may be minor, whereas others may be essential, depending on a particular case. This equation is usually applied in the integrated form, with an integration time period (day, season, year or decade) depending on applications (Chebotarev, 1975). In regions with polar climate, evaporation is a key component of the water (mass) balance of local lakes (Le et al., 2016; Leppäranta et al., 2020; Wang et al., 2020; Shi et al., 2024). The evaporation is, however, difficult to measure directly, and, therefore, it is estimated using indirect methods needing only a few meteorological and hydrological observations (Finch and Hall, 2001). The uncertainties of the indirect methods are often estimated relying on the eddy-covariance (EC) technique (Tanny et al., 2008; Tran et al., 2023; Shi et al., 2024) but is rarely used in Antarctica.

In hydrological applications, the evaporation over lakes is often evaluated using the empirical relationships between the evaporation, air-water moisture deficit, and wind speed (Keijeman, 1974; Finch and Hall, 2001) also known as combination formulas. They have been applied for the lakes in Antarctica even though their uncertainties are unknown (Borghini et al., 2013; Shevnina and Kourzeneva, 2017; Dhote et al., 2021). Many of these combination formulas, however, underestimate the evaporation over the local lakes by up to 72 %, and new empirical formulas need verification against independent measurements (Shevnina et al., 2022).

The bulk-aerodynamic method is often used to assess evaporation/sublimation over lakes and glaciers in Antarctica (Clow et al., 1988; Bliss et al., 2011; Leppäranta et al., 2016). In this method, the turbulent exchange (mass-transfer) coefficients, which is calculated incorporating empirical dimensionless gradient functions (Brutsaert, 1982). The empirical gradient functions can be evaluated from the eddy-covariance (EC) measurements on lakes (Franz et al., 2018; Ala-Könni et al., 2022). The bulk-aerodynamic method have not yet been suggested for the lakes in coastal Antarctica. In case, if the empirical gradient functions have been estimated for a boreal lake site, this method underestimated the summertime evaporation over an ice-free lake by over 32 % in Antarctica (Shevnina et al., 2022), and it is not clear how good it is for the lakes during the ice break-up period.

The study aims to quantify uncertainties of the combination equations and bulk-aerodynamic method applied for lakes in the coastal Antarctica, and to verify methods with independent observations. We estimated the evaporation over two lakes in the Schirmacher Oasis using the micrometeorological (eddy-covariance) and hydrological measurements collected in two austral summers in 2017–2018 and 2019–2020.

2 Study area

The Schirmacher Oasis (70°45′ S, 11°38′ E) is situated approximately 80 km from the coast of Lazarev Sea, Dronning Maud Land (Fig. 1 a). The oasis is an ice-free rock outcrop approximately 20 km long and 3 km wide (Fig. 1 a), engolated in the west–northwest to east–north-east direction (Simonov and Fedotov, 1964). The relief is hillrocks with absolute heights up to 228 m above sea level (asl). The rock hills mostly consist of gneiss mixed with basalts (Sengupta, 1991).

Antarctica is characterized by gravity-driven katabatic winds which play a key role in the regional climate, affecting sea ice formation, distribution of atmospheric moisture and precipitation in Antarctica (Nygård et al., 2013; Grazioli et al., 2017; Naakka et al., 2021), and enhancing the sublimation/evaporation over local lakes (Dugan et al., 2013; Leppäranta et al., 2016). The region of the Schirmacher Oasis is featured by the katabatic winds (Richter and Bormann, 1995). The maximum wind speed reaches up to 38 m s^{-1} in the austral winter (June – August) when the air temperature ranges from −4.5 to −12.9 °C (Govil et. al., 2016). During December – February, the average wind speed is 8.0 m s^{-1}, and the average accumulated precipitation is less than 10 mm water equivalent, falling as snow (Asthana et al., 2019).

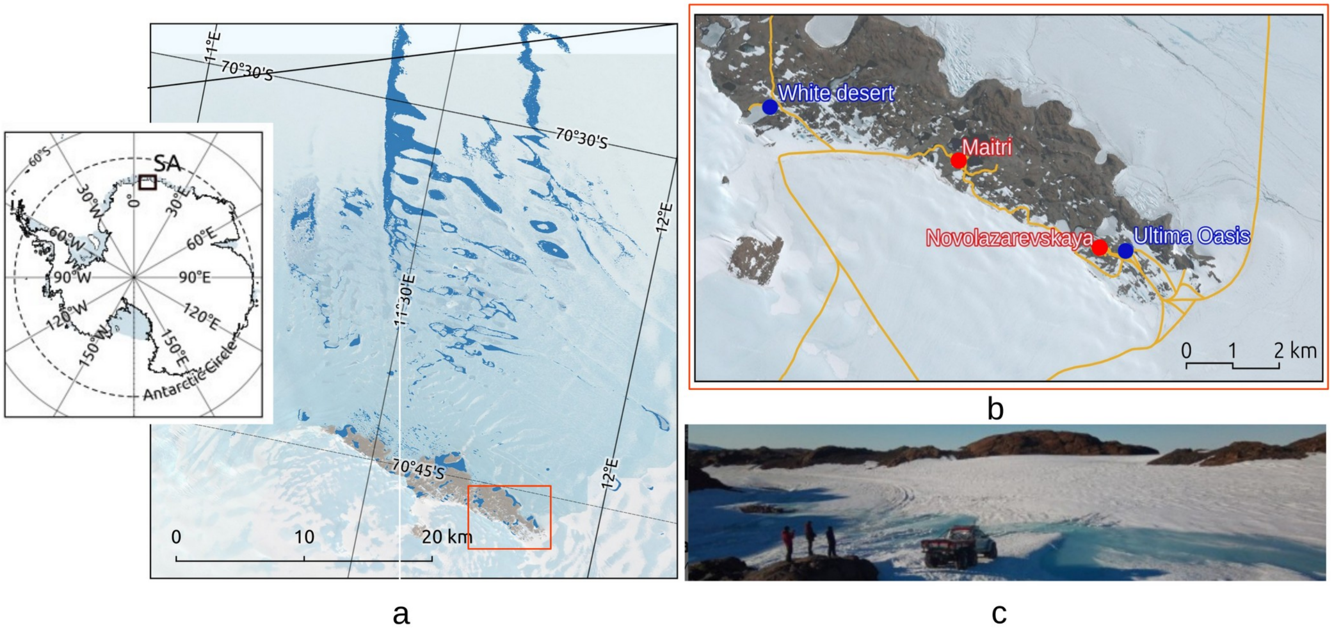

Fig. 1. Location of the Schirmacher Oasis (SA) (a) and its social infrastructure (b): year round (red dots) and seasonal (blue dots) settlements connected by roads (yellow lines, © Humanitarian OpenStreetMap Team (HOT), 2020. Distributed under the Open Data Commons Open Database License ((ODbL) v1.0.). © Google Maps, 2019. The red boxes in (a) and (b) outline the area with the main infrastructure in SA, and the image (c) shows the melted ice road to the White Desert Camp in December 2019 (photo by D. Emelyanov).

The oasis shelters two scientific bases operated year round (red dots, Fig. 1 b), and two tourist camps occupied seasonally (blue dots, Fig. 1 b). The scientific bases are occupied by 25 – 30 overwintering personnel, and up to 50 personnel during summer seasons. Up to 200 people can visit two tourist camps during summer. Two ice runways support transportation of people and cargo. Fuel and goods are mostly delivered by ships to coastal bases located on the ice shelf, and then transported to the settlements by vehicles. The settlements, ice runways and coastal bases are connected with year-round ice roads (yellow lines in Fig. 1 b). In summertime, the transportation along the ice roads is hindered by melted lakes and temporal streams formed over the ice surface. Figure 1 c shows the melted ice road to the White Desert Camp in December 2019.

More than 300 surface lakes in the Schirmacher Oasis are documented in the SCAR Antarctic Digital Database (Gerrish et al., 2020). Most of these lakes are freshwater water bodies feed by snow/ice melt, and free of ice for 6 – 12 weeks in the summer; the large lakes are connected in a chain by ephemeral streams (Sokratova, 2011; Phartiyal et al., 2011). This study focuses on the evaporation over two lakes differing in their surface area and depth. Lake Zub/ Priyadarshini is a water body with a maximum depth of 6.0 m (mean depth is 2.9 m), and a surface area of 35000 m^2 (Dhote et al., 2021). This lake often stayed free of ice during 6 – 8 weeks during the austral summer (Khare et al., 2008), and it was ice free from 29 – 31 December 2017 to 8 – 12 February 2018 and from 22 – 25 December 2019 to 10 – 14 February 2020. Lake Glubokoe has a maximum depth of 34.5 m (mean of depth is 13.1 m) and the surface area of 147000 m^2 (Loopman et al., 1988). The lake is normally ice-covered year round (Kaup, 2005), but in recent years the lake has been ice free almost every summer (Sharov and Tolstikov, 2020). In February 2018 and 2020 the lake was ice free for 2 – 3 weeks.

3 Data and methods

3.1 Micrometeorological and hydrological observations

The air temperature, atmospheric pressure, wind speed/direction, and water vapour concentration were measured on a tower equipped with the EC open-path system IRGASON by Campbell Scientific. These measurements were collected on two lakes (Fig. 2 a) in two different experiments covering 38 days in 2018 and 33 days in 2019 – 2020. In the first experiment on Lake Zub/Priyadarshini, the evaporation was measured during the period from 1 January to 8 February 2018 when the lake was free of ice. The second experiment on Lake Glubokoe covers the period from 7 December 2019 to 8 January 2020. The experiment was planned to be carried out over the duration of the austral summer, but our eddy-covariance instrumentation was damaged in mid-January. Hence, the actual measurements on Lake Glubokoe only represented the ice break-up period.

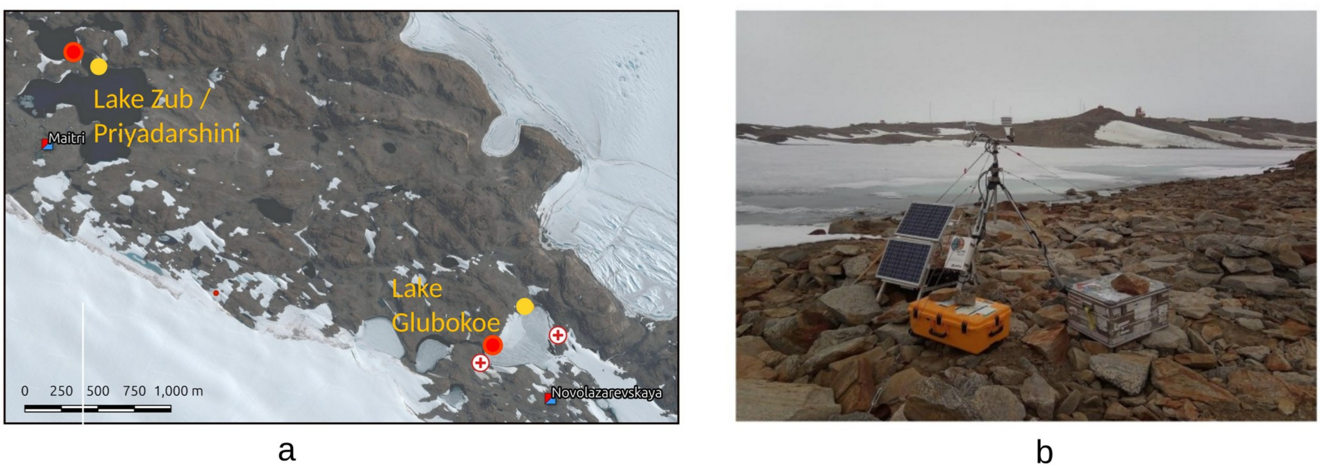

Figure 2. Location of the instrumentation on the shores of two lakes (a): temperature and water level logger (red dots), the EC system (yellow dots), and digital cameras collecting the panoramic images (rounded red crosses), © Google Maps 2019. The photo on (b) shows the EC system installed on the shore of Lake Glubokoe (12 December 2019).

The lake surface water temperature (LSWT) was measured by a research-grade data logger HOBO (red dots in Fig. 2 a), which record the pressure and temperature every 30 minutes with the accuracy ±0.44 degree (https://www.onsetcomp.com/products/data-loggers/u20l-0x). The HOBO logger was installed at a depth of 0.02 m. The measurements of LSWT cover the period from 8 December 2019 to 12 February 2020. The ice over the lake was documented in series of panoramic images taken by a digital camera (red crosses in Fig. 2 a). Shevnina et al. (2022) gives detailed information on the instrumentation used in the experiments.

3.2 Methods

The EC technique (Burba, 2013) was used to measure evaporation from the two lakes. The raw measurements were post-processed following Potes et al. (2017). The data were processed to remove spikes (Vickers and Mahrt, 1997), and the spikes detected were counted for quality control. The EC instrumentation collects the gas concentration in 0 – 360° wind directions, but the only data from the lake sector of the footprint was accounted for in the calculations. The measurements were filtered by the footprints defined according to Kljun et al. (2004). The air relative humidity and saturation vapor pressure deficit (corresponding to the difference between air and water temperatures) were calculated following Hoeltgebaum et al. (2020) and (Stull, 2017), respectively.

To calculate the daily evaporation over Lake Glubokoe, we applied the following combination equations, which read as follows: $E = 0.26(1 + 0.54\ w_2)(e_s - e_2)$ based on Penman (1948) and Tanny et al. (2008), $E = 0.26(1 + 0.86\ w_2)(e_s - e_2)$ according to Doorenbos and Pruitt (1975), and $E = 2.909A^{-0.05}w_2(e_s - e_2)$ according to Shuttleworth (1993). We also used the formula $E = 0.14(1 + 0.72w_2)(e_s - e_2)$ suggested for evaporation over lakes in northern Russia (Odrova 1979), and $E = -0.33(1 - 1.82w_2)(e_s - e_2)$ suggested based on the direct measurements over Lake Zub/Priyadarshini (Shevnina et al. 2022). In these equations, E is the evaporation in mm day^{-1} , A is the surface area in m^2, w_2 is the 2 m wind speed in m s^{-1}, e_s is the saturation water vapour pressure for a lake surface temperature, and e_2 is the water vapor pressure at the height of 2 meters. Both e_s and e_2 are in hPa, and calculated according to the Tetens's formula given in Stull (2017).

In the bulk-aerodynamic method, where the evaporation is defined as the vertical surface flux of water vapor due to atmospheric turbulent transport, calculated on the basis of the difference in specific humidity between the surface (ice or water) and the air (Brutsaert, 1985). In our study, the evaporation was calculated as follows:

$$E = \rho C_{Ez}\, w_z\, (q_s - q_{az}) \tag{1}$$

where E is the evaporation (kg m^{-2} s^{-1}); ρ is the air density (kg m^3), C_{Ez} is the turbulent transfer coefficient of moisture, q_s is the saturation specific humidity corresponding to a lake surface temperature (kg kg^{-1}), q_{az} is the air specific humidity (kg kg^{-1}), and w_z is the wind speed (m s^{-1}). The subscript z refers to the observation height. The turbulent transfer coefficient of moisture was calculated following the parametrization schemes suggested by Heikinheimo et al. (1999), Andreas (1986), Arya (1988) for the values corresponding to neutral stratification in the atmospheric surface layer (C_{ENz}). The effect of stratification in the atmospheric surface layer was taken into account following Launiainen and Vihma (1990) to convert C_{ENz} to C_{Ez}. The new wind-dependent relationship was derived by applying Eq. (1) on the basis of data on the evaporation, wind speed, air specific humidity and surface saturation specific humidity available from the experiment on Lake

Zub/Priyadarshini. The values by Heikinheimo et al. (1999) were given for z = 3 meters, and converted to our observation height of 2 m using the method by Launiainen and Vihma (1990).

We estimated the evaporation over the lakes on the basis of five combination formulas and four different parametrizations used for the transfer coefficient of moisture in the bulk-aerodynamic equation. The estimates based on these nine formulas were compared to the direct EC measurements (the reference). The reference was assumed to give the most accurate estimates for the evaporation with the instrumental error not exceeding 7 % for our EC system (Shevnina et al., 2022). To evaluate the skill of the indirect methods we apply the root mean square error ($RMSE = \sqrt{\sum_{1}^{n} \left(E_{EC} - E_{mod}\right)^2}$) following Moriasi et al. (2007). To define if a method is acceptable to be used in hydrological practice or not, we applied the s/σ criteria following to Popov (1979). In s/σ criteria: $s = \sqrt{\sum_{i=1}^{n} \left(E_{EC}^{i} - E_{mod}^{i}\right)^2 / (n-m)}$ and $\sigma = \sqrt{\sum_{i=1}^{n} \left(E_{EC}^{i} - \bar{E}_{EC}\right)^2 / n}$ where, E_{EC} is evaporation based on the EC method (mm d^{-1}), E_{mod} is evaporation based on an indirect method (mm d^{-1}); $\bar{E}$ is the mean evaporation, (mm d^{-1}); n is the length of the series, and m is the number of empirical coefficients in the relationships (equal to 2 in our case). We calculated the mean daily evaporation $\bar{E}$, and its error ($\sigma_{\bar{E}} = \frac{\sigma}{\sqrt{n}}$), and the results were shown as $\bar{E} \pm \sigma_{\bar{E}}$.

4 Results

4.1 Meteorological conditions, lake surface water temperature and lake ice cover

During the experiment on Lake Zub/Priyadarshini, the weather was colder and less windy than the climatology over 1961 – 2010, estimated according to the observations at Novolazarevskaya meteorological site (Shevnina et al., 2022). In January – February 2018, the daily mean air temperatures ranged between –5.6 and 2.4 ºC (Fig. 3 a, pink sold line). The daily mean wind speed varied between 1.3 to 13.2 m s^{-1} (Fig. 3 b, dark green solid line) with an average of 6.3 m s^{-1}. The mean daily relative humidity was 54 % and it varied from 39 to 77 % (Fig. 3 b, dark green solid line); it was higher than 90 % on 3 January and 2 December 2018.

During the experiment on Lake Glubokoe, the daily mean air temperature ranged from –1.4 ºC to 2.6 ºC (Fig. 3 a, red sold line), with an average of 1.0 ºC. During the experiment days, the air temperature varied from –4.9 ºC (minimum of the daily minimum air temperature) to 5.1 ºC (maximum of the daily maximum air temperature). The warmest days were observed from the end of December 2019 to the beginning of January 2020. The daily mean relative humidity was 56 % on average, and it varied from 43 to 77 % (Fig. 3 b, light green solid line); it was higher than 90 % between 25 and 26 December 2019.

The daily mean wind speed ranged from 1.3 to 9.5 m s^{-1} (Fig. 3 c, light blue solid line), and took on 5.9 m s^{-1} on average. The strongest wind was up to 13.0 m s^{-1} on 9 December 2019 and 1 January 2020, and the weakest winds were less than 0.5 m s^{-1} on 21 – 22, 24 and 25 December 2019 and 3 January 2020.

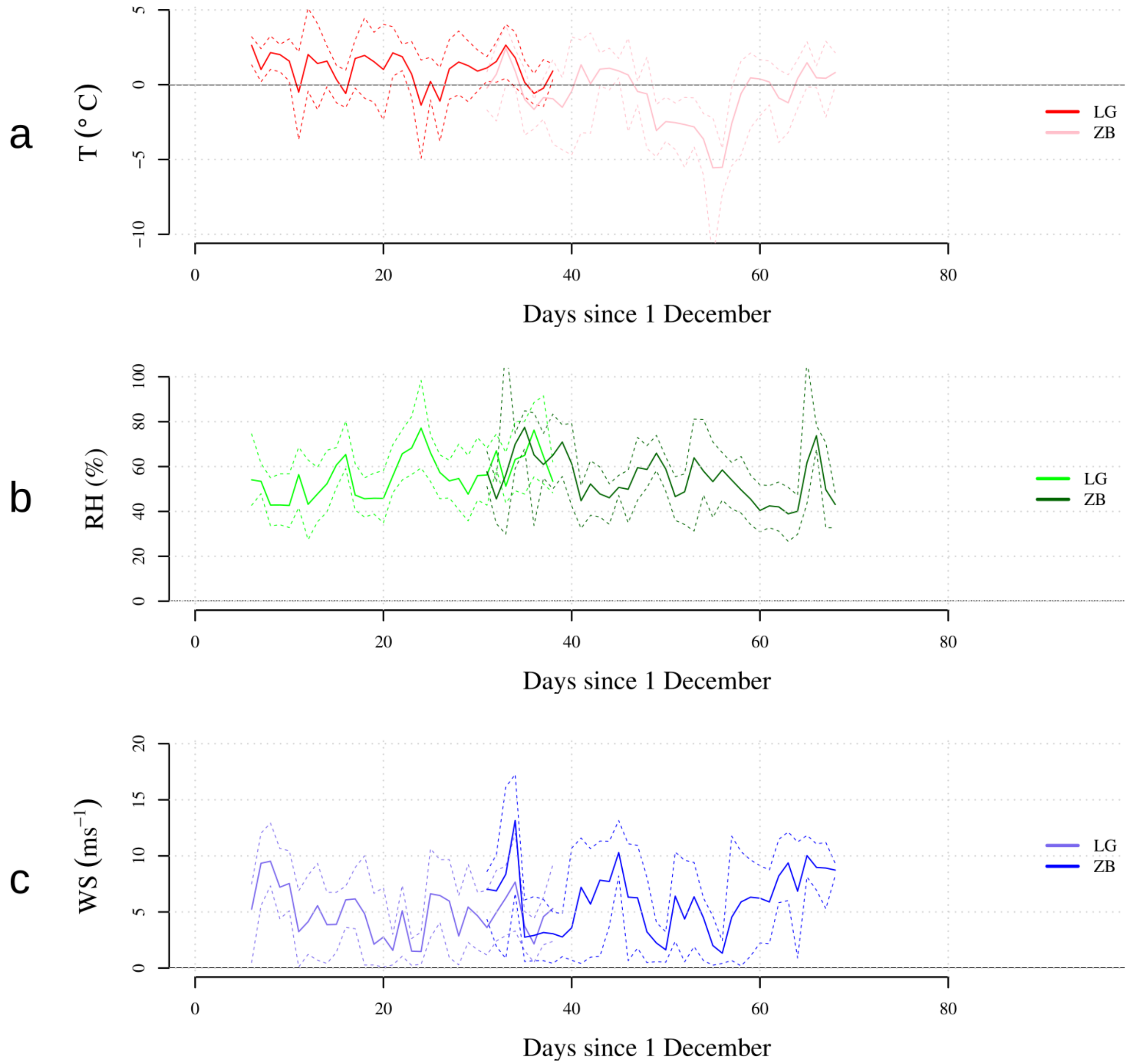

Figure 3: The mean (solid line), minimum and maximum (dashed lines) values for (a) the air temperature, (b) the relative humidity (b) and (c) the wind speed for the periods of the two experiments (horizontal axis is given in days starting from 1st December). LG refers to Lake Glubokoe and ZB to Lake Zub/Priyadarshini.

During most of the days in both experiments, the surfaces of Lake Zub/Priyadarshinis and Lake Glubokoe were warmer than the ambient air. During the period from 30 December 2018 to 9 February 2019, the mean daily LSWT in Lake

Zub/Priyadarshini was 3.9 ºC, which was 4.7 ºC higher than the mean air temperature (Fig. 4 a). The difference between the LSWT and air temperature varied from –0.5 ºC (2 – 3 January, 2018) to 10 ºC (25 – 26 January, 2018). From 7 December 2019 to 15 February 2020, the mean daily LSWT of Lake Glubokoe was 3.1 ºC (ranging from 0.6 to 5.3 ºC), and the lake was 2.4 ºC warmer than the air on average (Fig. 4 b). The largest difference between the temperature of air and lake water was observed on 26 December 2019 (–10 °C) when the wind speed was less than 1.0 m s^{-1} and the air relative humidity was over 95 % (Fig. 3).

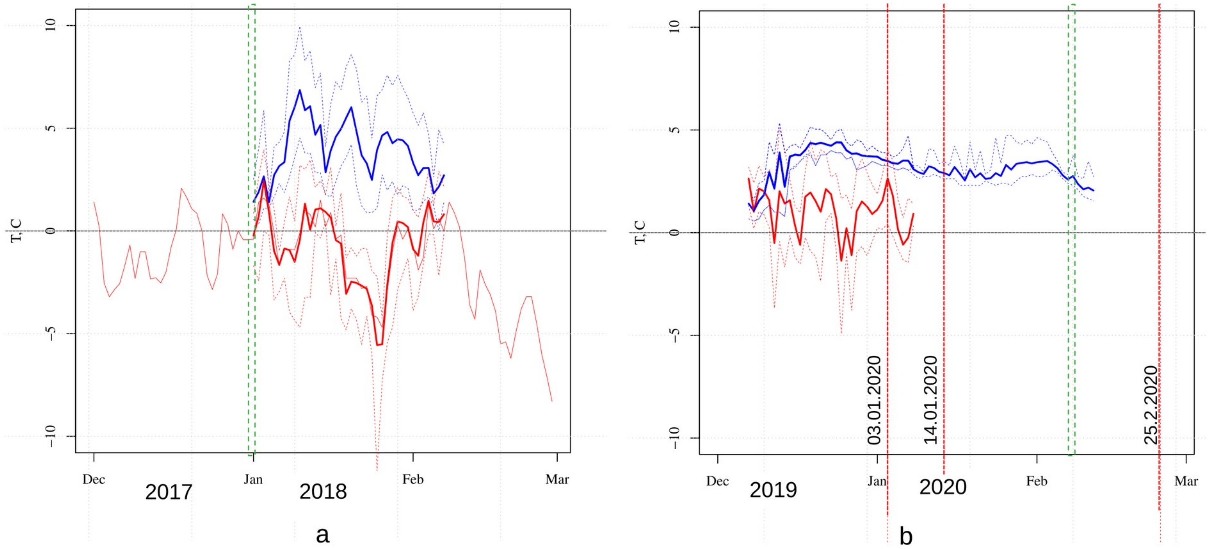

Figure 4. The daily minimum, mean and maximum for the air temperature (red lines) and LSWT (blue lines) measured during the experiments on Lake Zub/Priyadarshini (a) and Lake Glubokoe (b). In (a) the pink line shows the air temperature according to the observations at Maitri site, and in (b) the red lines show the dates of images given in Fig. 6 b-d. The green dashed lines show the days when the lakes became free of ice.

The diurnal cycle of the air temperature is qualitatively similar for both experiments: it reaches the maximum at the mid-day hours and the minimum at midnight. The average temperature was, however, higher in December 2019 – January 2020 (Fig. 5 a, coral boxplots) than in January – February 2018 (Fig. 5 a, light blue boxplots). The diurnal cycle of the LSWT differs between the two lakes: on Lake Zub/Priyadarshini LWST shows the nighttime (23:00 – 02:00) minimums of 3.0 ºC and daytime (12:00 – 14:00) maximums up to 6.0 ºC (Fig. 5 b, light blue boxplots), whereas on Lake Glubokoe, the LSWT showed a weaker diurnal cycle, LWST remaining close to 4.0 ºC (Fig. 5 b, coral boxplots).

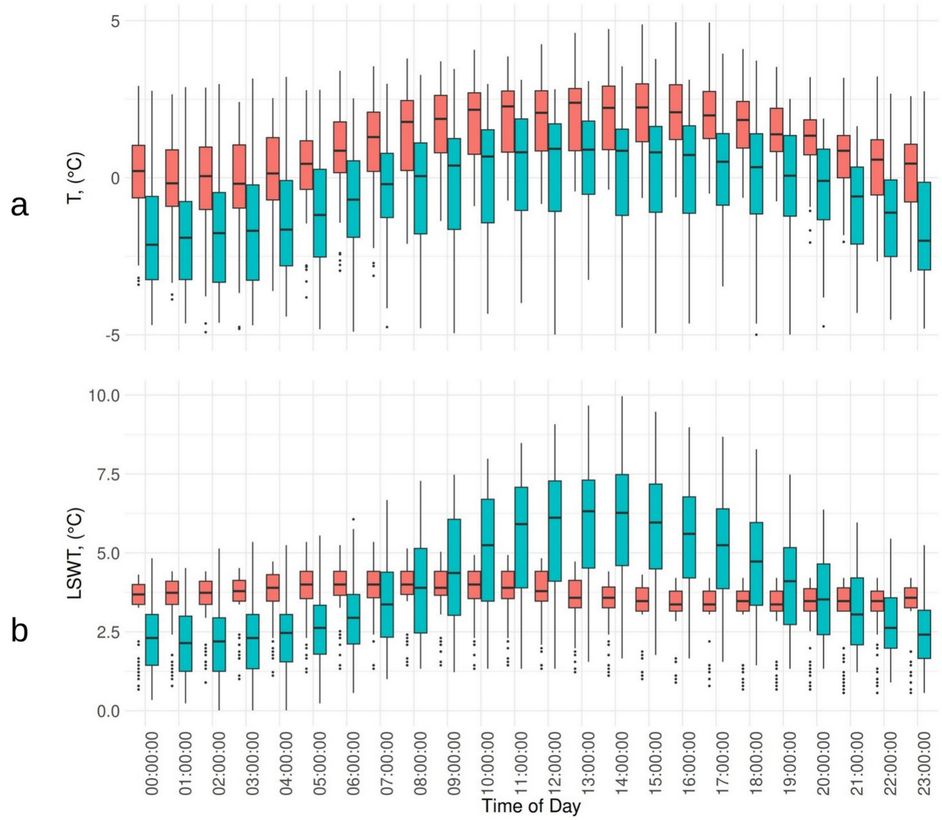

Figure 5. The diurnal cycles of air temperature (a) and the lake surface water temperature (b) measured on Lake Zub/Priyadarshini (light blue) and Lake Glubokoe (coral).

On Lake Glubokoe, the ice break-up period lasted from 8 – 12 December until 26 – 30 January; then, the lake stayed free of ice for approximately 2.5 weeks in February 2020. The lake ice cover was documented in a series of digital images taken from the three positions marked as Camera 1, Camera 2 and Camera 3 in Fig. 6 a. Figures 6 b and 6 c show the examples of the lake images taken on 3 January 2020 and 25 February 2020 using Camera 3 in the ice break-up stage (b) and the ice free stage (c). Fig. 6 d was taken 14 January 2020 from the position of Camera 1. The EC measurements were taken during those 33 days when the ice had melted from 30 – 35 % of the lake surface. The fraction of lake ice was evaluated by processing the digital images of the lake ice cover (taken every 5 – 10 days in the period of December 2019 – February 2020).

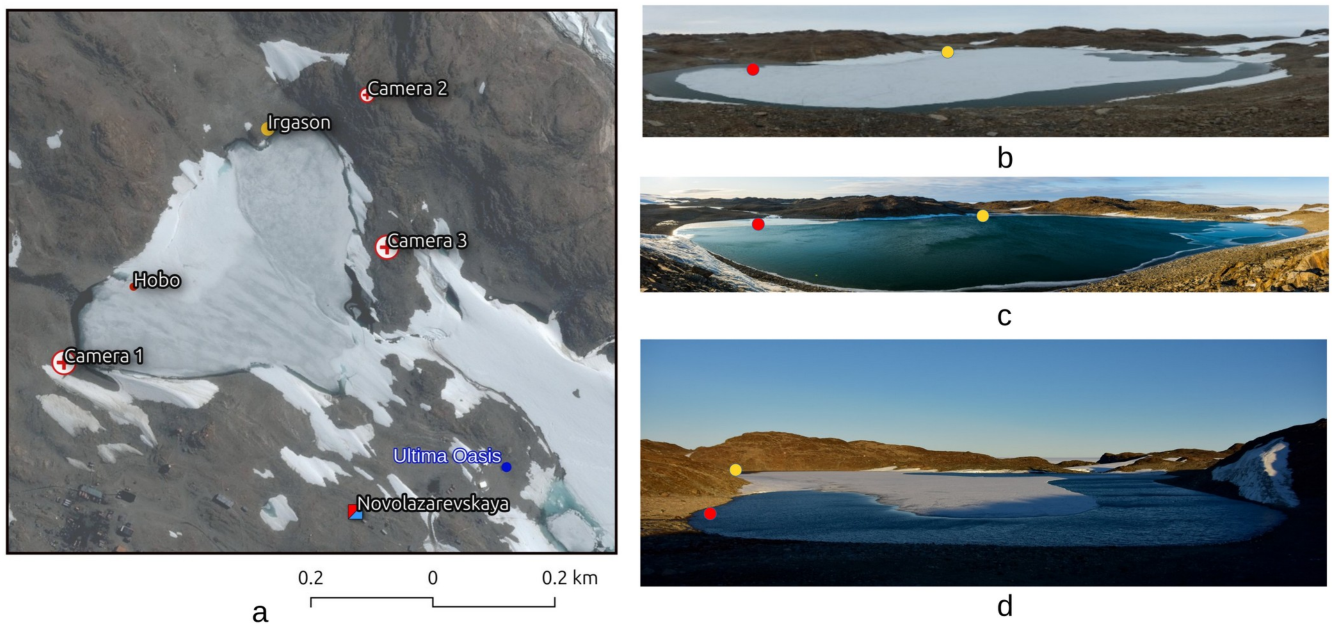

Figure 6. The instrumentation installed on Lake Glubokoe (a), *© Google Maps, 2019;* **(b, c and d) show the panoramic images of the lake location of the HOBO logger (red dot) and the EC system (yellow dot) on 3 January, 25 February and 14 January 2020 (photos by D. Emelyanov).**

4.2 Evaporation, the EC technique

Direct measurements of evaporation were a key component of this study. The EC system was installed on the shore of Lake Glubokoe in a location allowing it to cover the sector between 90 and 225 degrees and thus, to collect the measurements from the lake surface (Fig. 7 a). In Fig. 7 b, the X_{90} represents the horizontal distance over the lake surface that encompasses 90 % of the flux footprint, and it ranged from 50 to 150 m in the experiment on Lake Glubokoe.

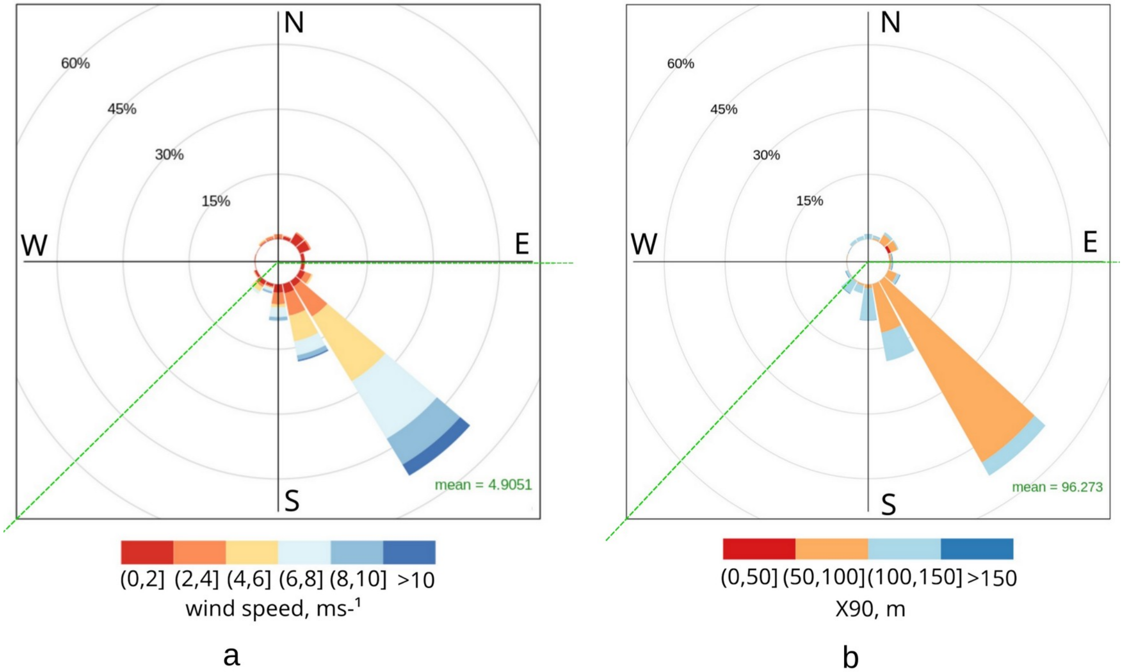

Figure 7. The wind roses (a) and length of the footprint (b) for the experiment on Lake Glubokoe. The green lines outline the sector of the wind directions covering the lake surface.

The raw 30-minute measurements were filtered by (i) the sensors’ signal strengths, (ii) number of gaps in the observations, (iii) the footprint, and (iv) the sector of wind directions covering the lake (Fig. 8 a, green lines). The percentage of the filtered data that was excluded did not exceed 20 % of total data (Fig. 8 b, red dots); most of the excluded data corresponded to wind directions outside the footprint. These gaps were replaced by the mean of evaporation estimated for the period of the experiment (Fig. 8 b, blue line). Since most of the gaps are lower than the mean, we also replaced them by the 25th percentile evaporation (Fig. 8 b, orange line).

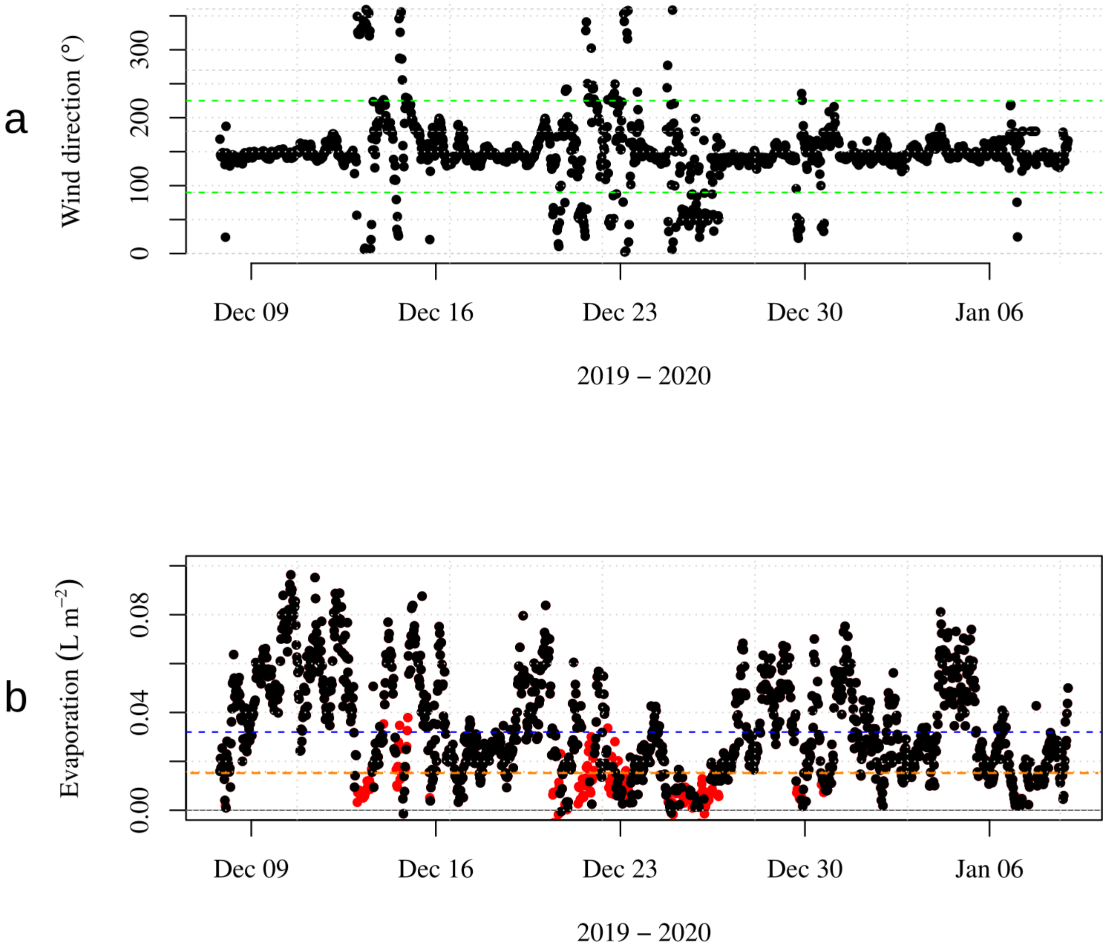

Figure 8. Time series of the 30-minute means of the wind direction (a) and evaporation (b) observed by the EC system on Lake Glubokoe. On (a): the green lines show the wind directions of 90 and 225 degrees (the footprint); on (b): the red dots indicate the measurements collected outside the footprint and the blue and orange lines show the mean and 25th percentile evaporation.

The daily evaporation was calculated from 30-minute measurements (with the gaps filled), and the total sum for the 33-day period of the experiment is 50 and 54 mm, when replacing the data gaps by the mean and 25th percentile, respectively. The daily mean evaporation was 1.5 ± 0.1 mm d^{-1} and 1.6 ± 0.1 mm d^{-1}, and it varied between 0.3 and 3.2 mm d^{-1}. These estimates show that filling the data gaps either by the mean or 25th percentile evaporation gave almost the same results. From here onward, we only present results where the gaps are filled by the mean. The largest evaporation (more than 2.5 mm d^{-1}) was observed on 9 – 11 December 2019 and 3 – 4 January 2020, and the lowest evaporation (less than 0.9 mm d^{-1}) was observed on 6 – 7 January 2020.

The diurnal cycle of evaporation over the lakes depends on the ice cover stage: it is larger during the ice-free stage on Lake Zub/Priyadarshini, when the evaporation reaches its maximum at the early morning between 06:00 and 07:00 (Fig. 9 a, light blue boxes). The diurnal cycle of evaporation is closely follows the cycle of wind speed (Fig. 9 c, light blue boxes). The strongest wind speed was observed at nighttime (03:00 – 04:00) reaching up to 10 m s^{-1}, while wind was often lower at daytime (16:00 – 17:00).

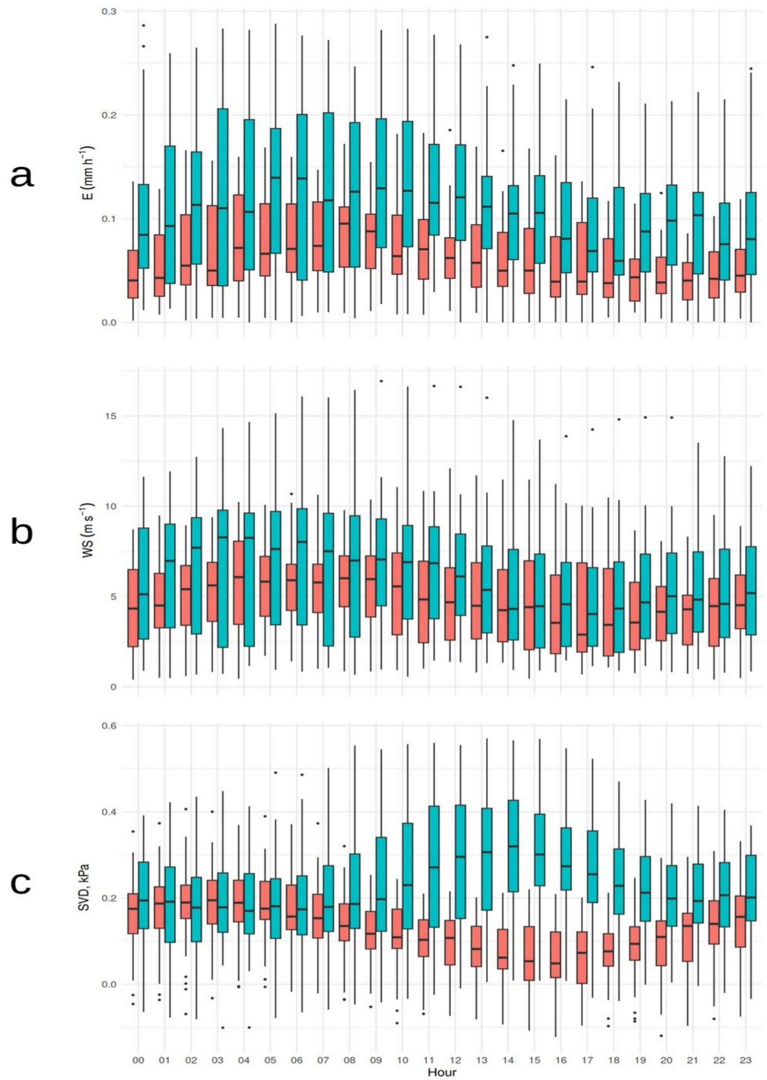

Figure 9. The diurnal cycle of (a) evaporation, (b) wind speed and (c) saturation vapor pressure deficit for the two experiments on Lake Zub/Priyadarshini (light blue) and Lake Glubokoe (coral).

The diurnal cycle of evaporation over the partly ice-covered Lake Glubokoe showed maximum (0.10 mm h^{-1}) in the early morning at 04:00 (Fig. 9 a, coral boxes), then reducing to even near-zero values in the late evening hours (21:00 – 23:00) and night. It was in the opposite phase relative to the diurnal cycle of the wind speed, demonstrating that the saturation deficit dominated over wind speed as the primary driver of evaporation (Fig. 9). These different patterns in the diurnal cycle of evaporation over the two lakes reflect the complex interplay of drivers (air-water temperature gradient, air humidity, wind speed, solar radiation) that vary throughout the day.

4.3 Evaporation, uncertainties of the indirect methods

The evaporation over Lake Glubokoe was estimated on the basis of five combination formulas (E_{CE} in Table 1). Considering the results of the first four formulas listed in Table 1, the mean daily evaporation varied between 0.4 ± 0.1 mm d^{-1} and 1.1± 0.1 mm d^{-1}, which represent 27 – 73 % less than the evaporation based on the EC method. The formula by Shevnina et al. (2022) gave only 6 % underestimation with respect to the evaporation measured by the EC technique. The *s/σ* of all combination formulas is higher than 2, and the RMSE varies between 1.3 and 1.6 mm d^{-1}.

Table 1. The evaporation over Lake Glubokoe on the basis of five combination formulas (E_{CE}, mm day^{-1}) and their skill scores. The bold numbers indicate the method with the best scopes.

Author(s) (year)	**E_{CE}, mm d^{-1}**		**Sum mm period^{-1}**	***E_{EC} / E_{CE}***	**skill scores**	
	Mean	**Max**			***RMSE***	***s/σ***
Penman (1948)	0.6 ± 0.1	1.6	20	2.7	1.3	2.1
Doorenbos and Pruitt (1975)	0.8 ± 0.1	2.4	28	1.9	1.5	2.4
Odrova (1979)	0.4 ± 0.1	1.1	13	4.1	1.3	2.2
Shuttleworth (1993)	1.1 ± 0.1	2.6	37	1.4	1.3	2.1
Shevnina et al. (2022)	**1.5 ± 0.2**	5.0	50	1.1	1.6	2.6

Furthermore, evaporation was estimated using the bulk-aerodynamic method. The neutral wind-dependent transfer coefficients, derived from observed evaporation, wind speed, air specific humidity, and surface saturation specific humidity over Lake Zub/Priyadarshini, are as follows:

$$C_{EN10} = 0.0000119\, w_2 + 0.00114\ (w_2 < 13 \text{ m s}^{-1}) \text{ and } C_{E10} = 0.0013\ (\text{if } w_2 >= 13 \text{ m s}^{-1}) \quad (2)$$

$$C_{EN2} = 0.0000193\, w_2 + 0.00153\ (\text{if } w_2 < 13 \text{ m s}^{-1}) \text{ and } C_{E2} = 0.0018\ (\text{if } w_2 >= 13 \text{ m s}^{-1}) \quad (3)$$

where w_2 is the wind speed (m s^{-1}) at the height of 2 m. Figure 10 shows the values of the transfer coefficients calculated for the standard height of 10 m.

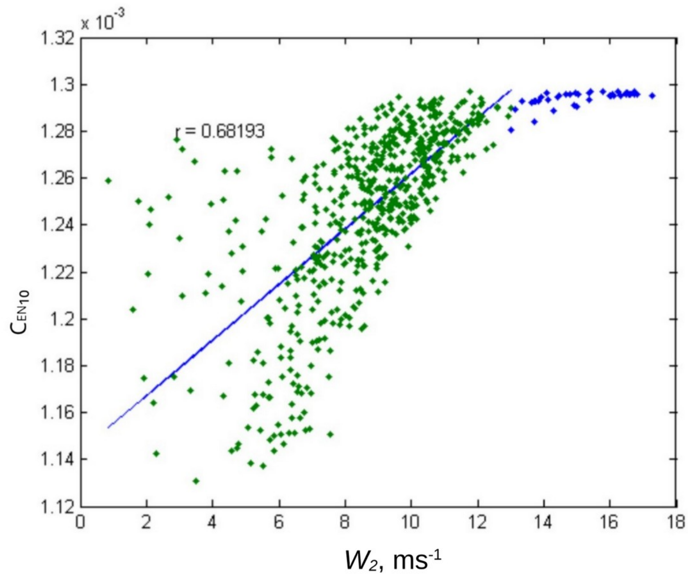

Figure 10. Dependence of the 10-m neutral transfer coefficient for moisture (C_{EN10}) on the 2 m wind speed (w_2, m s^{-1}) over Lake Zub/Priyadarshini (2017 – 2018).

We also calculated the neutral transfer coefficient of moisture on the basis of the measurements on Lake Glubokoe following Andreas (1986), Arya (1988) and Heikinheimo et al. (1999). The coefficient varied between 1.2 x 10^{-3} and 2.1 x 10^{-3} depending on the parameterization (Table 2). In Table 2, the transfer coefficients are presented for the measurement heights (different in the two experiments) and, to compare our results, also for the standard height of 10 meters (C_{EN10}).

Table 2. Transfer neutral coefficients for moisture (C_{ENz}) in the bulk-aerodynamic method. Notations: z refers to the height.

Parameterization scheme	C_{EN10}	Lake Zub / Priyadarshini	Lake Glubokoe
		z = 2 m	*z* = 1.8 m
Heikinheimo et al. (1999)	1.2 x 10^{-3}	1.0 x 10^{-3}	1.0 x 10^{-3}
Arya (1988)	1.4 x 10^{-3}	1.2 x 10^{-3}	
Andreas (1986)	2.1 x 10^{-3}	1.7 x 10^{-3}	
this study (wind dependent)	Eq. (2)	Eq. (3)	

Table 3 shows the daily evaporation estimated with four parameterizations for the transfer coefficient of moisture following Heikinheimo et al. (1999), Arya (1988), Andreas (1986) and this study (wind-dependent). Following these parametrizations, the mean daily evaporation varied between 2.0 ± 0.1 mm d^{-1} and 3.0 ± 0.2 mm d^{-1} in case of Lake Zub/Priyadarshini. The parametrization by Andreas (1986) gave the best estimate for the evaporation being 3.0 ± 0.2 mm d^{-1} on average. In the case of Lake Glubokoe, the best estimate for the evaporation being 1.5 ± 0.1 mm d^{-1} (on average) was obtained with the transfer coefficient based on Arya (1988) while the reference (EC) method assessed the evaporation as 1.6 ± 0.1 mm d^{-1} (ie. 8 % less than the Arya (1988)). Depending on the parametrization of the transfer coefficient of moisture, the bulk-aerodynamic method either overestimated the evaporation by up to 38 % or underestimated it by up to 20 %.

Table 3. Evaporation over the two lakes (E_{BA} mm d^{-1}) estimated using the bulk-aerodynamic method with four schemes of parametrization for the transfer neutral coefficient of moisture (C_{ENz}). The bold numbers indicate the indirect method that yielded the estimates closest to the reference.

Scheme	Lake Zub / Priyadarshini				Lake Glubokoe			
	Mean	Max	Sum, mm $period^{-1}$	E_{EC} / E_{BA}	Mean	Max	Sum, mm $period^{-1}$	E_{EC} / E_{BA}
Heikinheimo et al. (1999)	2.0 ± 0.1	3.5	75	1.6	1.3 ± 0.1	2.3	42	1.3
Arya (1988)	2.1 ± 0.2	3.8	79	1.5	**1.5 ± 0.1**	2.7	50	1.1
Andreas (1986)	**3.0 ± 0.2**	5.4	114	1.0	2.2 ± 0.2	3.9	71	0.8
this study (wind-dependent)	2.6 ± 0.2	4.8	100	1.2	1.9 ± 0.2	3.6	63	0.9

Figure 11 shows the daily evaporation estimated from the direct measurements (x-axis) against those estimated by the bulk-aerodynamic method using the parameterizations for the transfer coefficient of moisture which were calculated from the independent observations in each case. In Fig. 11 a, AN refers to the scheme suggested by Andreas (1986) and AF to Arya (1988) when the transfer coefficient was calculated from the EC measurements collected during the experiment on Lake Glubokoe. In Fig. 11 b, WD is the wind-dependent coefficient derived from the EC measurements collected on Lake Zub/Priyadarshini, and the experiment on Lake Glubokoe provided the independent measurements.

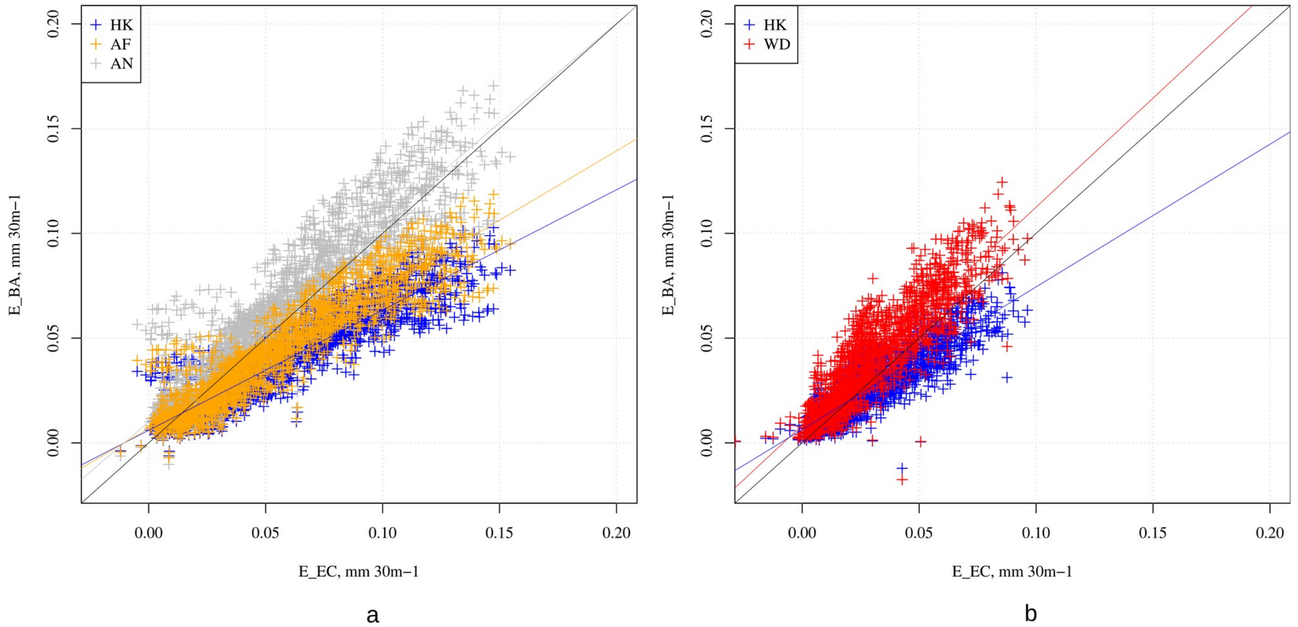

Figure 11. Evaporation based on the direct observations (x-axis) and estimates applying the bulk-aerodynamic method with different parameterizations for the transfer coefficient of moisture (y-axis): (a) Lake Zub/Priyadarshini and (b) Lake Glubokoe. Notations: HK refers to Heikinheimo et al. (1999), AN to Andreas (1986), AF to Arya (1988), and WD is the wind-dependent coefficient derived from the measurements collected from Lake Zub/Priyadarshini in 2017 – 2018.

Depending on the parametrization (model) applied for the transfer coefficient of moisture in the bulk-aerodynamic method, the root mean square error (RMSE) varied from 0.4 to 0.8 mm d^{-1} (Table 4). The *s/σ* criteria were less than 0.8 for two parametrization schemes, namely Andreas (1986) and Arya (1988), however, the averaged over the two lakes, the wind-dependent transfer coefficient gave the best skill scores.

Table 4. The skill scores of the bulk-aerodynamic method using various parameterizations for the transfer coefficient of moisture.

Parameterization schemes	Lake Zub / Priyadarshini		Lake Glubokoe	
	RMSE	***s/σ***	**RMSE**	***s/σ***
Heikinheimo et al., 1999	1.2	1.2	0.5	0.8
Arya (1988)	1.1	1.2	**0.4**	**0.7**
Andreas (1986)	**0.7**	**0.7**	0.8	1.2
Wind-dependent	0.7	0.7	0.5	0.9

It is indeed interesting that the new wind-dependent transfer coefficient, derived on the basis of Lake Zub/Priyadarshini data, has a smaller RMSE for Lake Glubokoe than for Lake Zub/Priyadarshini. This is, however, understandable because the transfer coefficient is only one of the factors that control the evaporation calculated using the bulk-aerodynamic formula (Eq. (1)). In addition to the transfer coefficient, at least the following factors may generate inaccuracy in the estimated evaporation: (1) errors in the measurements of lake surface temperature (controlling the saturation specific humidity), air specific humidity, and wind speed, (2) contribution of spray droplets to evaporation, (3) role of waves in the lake surface, and (4) validity of the Monin-Obukhov similarity theory, which requires quasi-stationary and horizontally homogeneous conditions. Errors and uncertainties associated with (1) – (4) above may either increase the overall error or partially offset one another. Hence, it is reasonable that the performance of parameterization schemes varies among lakes, as factors (1) – (4) may be site-specific, and also depends on the metrics used (e.g., RMSE or s/σ) to evaluate the performance (Table 4).

5 Discussion

This study yielded estimates of the uncertainties of the combination formulas and bulk-aerodynamic method, using as reference the direct eddy-covariance measurements collected on two lakes in the Schirmacher Oasis. The field experiments covered the ice-free and the break-up stages on the lakes differing in the surface area, depth and volume. During the ice break-up period, the evaporation over the large and deep Lake Glubokoe varied between 0.3 and 3.2 mm d^{-1}, with an average of 1.6 ± 0.1 mm d^{-1}. This corresponded to 54 mm of evaporation over 33-day period in December 2019 – January 2020. This is only slightly more than half of the evaporation over the ice-free Lake Zub/Priyadarshini, which averaged 3.0 ± 0.2 mm d^{-1} in January – February 2018. The highest evaporation was measured on 13 – 15 December 2019 on Lake Glubokoe (ice break-up stage) and 2 – 3 January 2018 on Lake Lake Zub/Priyadarshini (ice-free stage). The evaporation generally increased with wind speed, with the maximum of 5.0 mm d^{-1} observed during the wind storms. Over Lake Zub/Priyadarshini, the diurnal cycle of evaporation closely followed that of the wind speed cycle peaking at nighttime (23:00 –02:00) and lowing at daytime (12:00 – 14:00), but the cycle was weaker during the ice break-up stage (December) than the ice-free stage (January).

To the best of our knowledge, direct EC measurements of evaporation in Antarctica have only been conducted on lakes in the Schirmacher Oasis. However, similar measurements have been taken in regions with a polar desert climate, such as the high-altitudes lakes located in the Qinghai-Tibetan Plateau (36°N, 3194 m asl). Applying two years of observations, Li et al. (2016) found that evaporation over the ice-free Lake Qinghai reaches up to 12 mm d^{-1} during storms, and days with wind speed higher than 4 m s^{-1} contribute up to 22 % of the annual lake evaporation. Lately, based on the EC observations in 2014 – 2019, Shi et al. (2024) found that evaporation over an ice-free lake in the Qinghai-Tibetan Plateau was controlled by wind. The authors suggested that the ice sublimation contributes to 23 % of annual evaporation over Lake Qinghai. Our results show that the wind speed is the primary driver for the short-term variation of evaporation on Lake Zub/Priyadarshini, which contradicts with the results for the lakes in the Qinghai-Tibetan Plateau (Wang et al., 2019) where winds are weaker on average.

Leppäranta et al. (2016) estimated the mean summertime sublimation/evaporation from ice-covered and ice free lakes in the Vestfjella mountains, Droning Maud Land (73°S) to be 0.7 mm d^{-1}. Further, Leppäranta et al. (2016) associated events of large lake ice thinning on a small pond to strong local winds exceeding 30 m s^{-1} in the absence of surface melt: in such conditions the ice sublimation reached of 10 – 15 mm d^{-1}. No EC observations were available from the site but we checked that according to the bulk-aerodynamic method these values are indeed possible under such a wind speed, if the ice surface temperature is close to 0 ºC and the air is very dry. Dugan et al. (2013) estimate that the lake ice ablation (sublimation) over three ice-covered lakes in Tailor Valley, East Antarctica (77°S) is 5 – 31 mm d^{-1}, but the authors did not have means to distinguish between the contributions of surface melt and sublimation to ablation during summer. For winter, Dugan et al. (2013) found sublimation values ranging from 0.2 to 0.7 mm d^{-1}. These values for ice-covered lakes in winter are naturally much smaller than our results for mostly ice-free lakes in summer.

The mass and energy balance method, the bulk aerodynamic method, combination formulas, the equilibrium temperature method, empirical formulas, pans and tracers (water isotopes) are among the indirect methods often used to estimate evaporation over lakes and reservoirs (Abtew and Melesse, 2013; Bellagamba et al., 2021). Finch and Calver (2008) have shown that each method has its strengths and weaknesses allowing application in various geographical locations; nevertheless, no suggestions for the indirect method has been presented for Antarctica. The evaporation over lakes is often evaluated applying combination formulas, and we found five combination formulas (Penman, 1948; Doorenbos and Pruitt, 1975; Odrova, 1979; Shuttleworth, 1993; and Shevnina et al., 2022) that have been applied over lakes in Antarctica.

Our results showed that the Penman's formula (1947) underestimated the lake evaporation by 57 – 60 %. The formulas by Shuttleworth (1993) and Doorenbos and Pruitt (1975) underestimated the daily evaporation by 27 % and by 47 % on average, respectively. The formula by Odrova (1979) underestimated the daily evaporation by 72 – 73 %. This formula has been used to estimate the summertime evaporation over 12 lakes in the Larsemann Hills Oasis (LHO), East Antarctica (69 °S) and King George Island (69 °S), where evaporation varies between 0.8 and 1.7 mm d^{-1} depending on the LSWT and presence of the lake ice cover (Shevnina and Kourzeneva, 2017). In the case of Lake Glubokoe, this formula yielded an average evaporation of 0.4 mm d^{-1}, which is less than for the lakes in LHO. This difference, however, can be explained by the fact that the observations on Lake Glubokoe cover the early stage of the lake ice break-up period in December, while the observations on the lakes in LHO were carried out in January – February when over 60–80% of the lake surface was ice free. The formula by Shevnina et al. (2022) underestimated the daily evaporation over the lake during the ice-break up stage by 6 % on average compared with direct EC observations. For all combination formulas, the methods' skill scores were low (s/σ >> 0.80 and RMSE was 1.4 mm d^{-1} on average).

The bulk-aerodynamic method is often used to estimate the surface evaporation; this method is, however, sensitive to a function defining the transfer coefficient of moisture. It is typically considered almost constant with a value of approximately 1.1 x 10^{-3} over the ocean (Kantha and Clayson, 2000) and varying between 1.1 x 10^{-3} and 2.4 x 10^{-3} over the lakes and reservoirs (Hicks, 1972). As the transfer coefficient depends on the surface roughness lengths, its values are site specific but do not explicitly depend on a lake surface area and depth (Guseva et al., 2023). The bulk-aerodynamic method using the parametrization derived based on observations in a boreal lake underestimated the evaporation over the ice-free Lake Zub/Priyadarshini by over 30 % (Shevnina et al., 2022). Our results showed that the transfer coefficient of moisture derived according to Arya (1988) or Andreas (1986) allowed reduction of the uncertainties of the bulk-aerodynamic method, which underestimated the evaporation by only 6 – 8 % in these cases. With the transfer coefficient of moisture varying between 1.4 x 10^{-3} and 2.1 x 10^{-3}, this method demonstrated the following skill scores: $s/\sigma < 0.80$ and average RMSE of 0.6 mm d^{-1}. Our results showed that in general the mass transfer methods work well enough to reproduce the evaporation over the lakes in the Schirmacher Oasis , and this is aligns with outcomes from the studies focused on the evaporation over the high-altitude lakes of Qinghai-Tibetan Plateau (Wang et al., 2019).

The measured (EC) evaporation includes the contributions of both interfacial evaporation from the lake surface and evaporation from spray droplets in the air. It is difficult to distinguish between these contributions but, based on observations by Guest (2021) over the Southern Ocean, we may assume that under very strong winds the spray evaporation is some 18 % of the interfacial evaporation. Accordingly, if one wants to apply the wind dependent transfer coefficient (Eqs 2, 3) solely for the interfacial evaporation, the contribution of spray evaporation must be subtracted from the results. The stability dependence for the transfer coefficient of moisture was minor. This was because during the period of the experiments, the lakes were continuously warmer than the ambient air (on average by 4.7 C in January – February 2018). Hence, when the wind was strong, the stratification was close to neutral and the transfer coefficient was large and not sensitive to the stratification.

The method used in calculations of evaporation is important for the Antarctic coastal lakes whose volume changes very little over an austral summer (Shevnina and Kourzeneva, 2017). Applying the method of water isotopes, Gopinath et al. (2020) found the importance of summertime evaporation in the water balance of the shallow lakes in the Schirmacher Oasis, and Lake Zub/Priyadarshini is one of such lakes. This lake water supplies the Maitri research station (opened in the late 1980s) and the new Maitri-II observatory (planned to opened in 2029). The lake's water balance equation includes the precipitation and inlet river runoff (as inflow/positive components); and the outlet river runoff, evaporation and water withdrawal (as outflow/negative components). The lake volume is 1032500 m^3, and in January-February 2018 it decreased by 40.3 m^3, and the discrepancies of the water balance equation was 670.6 m^3 (Dhote et al., 2021). The lake evaporation of 58.5 m^3 was calculated following Odrova (1979), which underestimated the evaporation by 72 % according to our results. In absolute values it corresponds to 42.1 m^3 (58.5 multiplied by 0.72), which represents approximately 6 % of the discrepancy of the water balance equation. It can be reduced by using a better indirect method while calculating the evaporation. For a better method we suggested the bulk-aerodynamic method with the neutral 10-m transfer coefficient of moisture (C_{ENz}, z = 10 m) equaling to 2.1 x 10^{-3}. The volume of precipitation over the lake was 5.3 m^3 in January – February 2018, which is a negligible component in the lake water balance equation, only representing 0.05 % of the lake volume. The rest of discrepancy is connected to the methods used to evaluate the inlet/outlet river runoff.

When air is heated and moistened over a lake surface and then advected to over colder ice-covered surface, its temperature and dew-point temperature decrease, often leading to formation of local fog (Gultepe et al., 2003) and even precipitation (Su et al., 2020). In the Schirmacher Oasis, fog was observed in the early morning of 26 December 2019 (Fig. 12). Such fogs promote ice surface melt, decrease visibility, and endanger transport operations between settlements, ice runways and coastal bases. Our next study will addressed development of methods to better foresee such events.

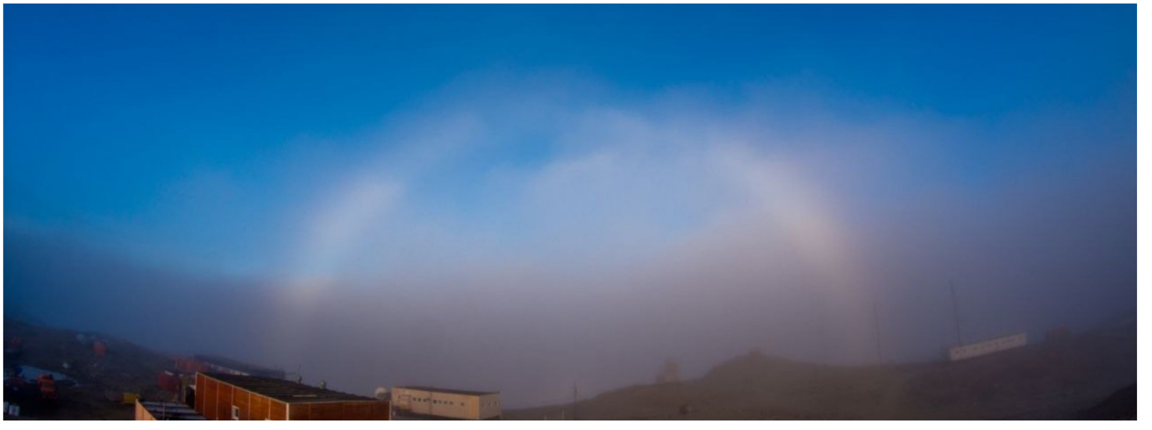

Figure 12. The fogbow was observed in the early morning hours on 26 December 2019 in the Schirmacher Oasis (photo D. Emelyanov).

This study focused on the direct physical drivers of evaporation from lakes: surface temperature, which determines the saturation specific humidity and saturation water vapor pressure; air humidity, expressed as specific humidity or vapour pressure; as well as wind speed and air temperature, which govern turbulent exchange. Considering the broader causal chain, several factors act as indirect drivers of evaporation. These include atmospheric circulation patterns, affecting wind fields, air temperature and humidity, as well as solar radiation. Solar radiation is at the beginning of this causal chain, controlling both the surface energy balance and the melt processes that generate glacial lakes and streams. Solar radiation is explicitly included in the energy balance method used to estimate, but in our experiments it was not measured.

6 Conclusions

We quantified uncertainties associated with the bulk-aerodynamic method and combination formulas applied in estimations of summertime evaporation over two lakes in coastal Antarctica. The direct measurements by the EC method showed that summertime evaporation varied from 0.3 to 5.0 mm d^{-1}. Depending on the presence of lake ice, the mean daily evaporation varied from 1.6 ± 0.2 mm d^{-1} in the early stage of ice break-up (December) to 3.0 ± 0.3 mm d^{-1} for the ice-free stage (January – February). During the austral summer, the surface lakes are warmer than the ambient air on most days, and the difference between the temperature of air and lake water reaches up to 10 °C during calm days. The changes in evaporation were associated with changes in wind speed rather than changes in difference between the near-surface air temperature and lake surface water temperature.

The bulk aerodynamic method yielded the most accurate estimates of evaporation (biases of 6 – 8 % for the mean values) when the neutral transfer coefficient of moisture (C_{ENz}, z = 10 m) was set to 2.1 x 10^{-3} and 1.4 x 10^{-3} for Lake Zub/Priyadarshini and Lake Glubokoe, respectively. This method showed an acceptable skill in estimating daily evaporation over both lakes in the Schirmacher Oasis during their ice break-up and ice-free stages. Hence,we recommend this method for use in hydrological applications and by water managers for operational decision-making.

The selected combination formulas underestimated the daily evaporation over the lakes in the Schirmacher Oasis by 27–73 %. With the correction, however, they can be applied to estimate the cumulative summertime evaporation, which is needed for the hydrological applications required for decisions on sites' maintenance and investment. These indirect methods need the measurements of lake surface water temperature.

Code availability. The code is available at https://github.com/ElenaShevnina/Lake-Evaporation. The code for the figures 3, 4, 5, 8, 9 and 11 was written using suggestions given by the Github Copilot (Artificial Intelligence).

Data availability. The dataset is available at https://doi.org/10.5281/zenodo.14823402.

Interactive computing environment. Pycharm at Ubuntu (Noble Nombat).

Supplements. The data and results are given at https://github.com/ElenaShevnina/Lake-Evaporation.

Author contribution. ES designed and performed field experiments as well as calculated evaporation from combination equations, methods' uncertainties and skill scores. TV estimated evaporation with the bulk-aerodynamic method and suggested the wind-dependent parametrization for the transfer coefficient of moisture. MP designed, analyzed the EC measurements in the field experiments, and implemented the parametrization of the transfer coefficient of moisture from the experiment on Lake Glubokoe. TN analyzed weather during the experiments. All authors contributed to writing of the manuscript.

Competing interests. The contact author has declared that none of the authors has any competing interests.

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