Evaporation over glacial lakes in Antarctica

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Abstract. The study provides estimates of summertime evaporation over the ice-free surface of Lake Zub/Priyadarshini located in the Schirmacher oasis, Dronning Maud Land, East Antarctica. Lake Zub/Priyadarshini is the second largest lake in the oasis; its maximum depth is 6 m. The lake, among the warmest glacial lakes, is free of ice for almost two summer months. The summertime evaporation over the lake's open water table was estimated after applying the eddy covariance (EC) method, the bulk-aerodynamic method and Dalton type empirical equations. We used special meteorological and hydrological measurements collected during the field experiment carried out in 2018 in addition to the standard observations at the nearest meteorological site. The EC method was considered the most accurate, given a reference for other estimates of evaporation over the lake water surface. We estimated the evaporation over the ice-free lake surface as 114 mm in the period from 1 January to 7 February, 2018 (38 days) after the direct EC method. The average daily evaporation is estimated to be 3.0 mm day^{-1} in January 2018. The largest changes in the daily evaporation were driven by the synoptic-scale atmospheric processes rather than local katabatic winds. The bulk-aerodynamic method suggests the average daily evaporation to be 2.0 mm day^{-1}, which is over 30 % less than the EC method. This method is much better in producing the day-to-day variations in evaporation compared to the Dalton type semi-empirical equations, which underestimated the evaporation over the lake's open water table by over 40–72 %. We also suggested a linear empirical relationship to evaluate the summertime evaporation of Lake Zub/Priyadarshini from the observations at the nearest meteorological site and at the surface water temperature. After applying this method, the evaporation over the period of the experiment was 120 mm, only 5 % larger than the result according to the EC method. We also estimated the daily evaporation from the ERA5 reanalysis, which suggested the average daily evaporation during the austral summer (December–February) 2017–2018 to be 0.6 mm day^{-1}. It was only one-fifth of the evaporation estimated with the direct EC method.

1 Introduction

Liquid water is increasingly more present over the margins of glaciers, ice sheets, and the surface of the Arctic sea ice and Antarctic ice shelf as near-surface air temperature is rising. A large part of melt water accumulates in a population of glacial lakes (Golubev, 1976; Hodgson, 2012). The glacial lakes are typical for the lowermost (melting) zone of glaciers and ice sheets, where the amount of liquid water is sufficient for surface/subsurface runoff (Golubev, 1976). The area of the melting zone is evaluated from in-situ data gathering during glaciological surveys or from remote sensing data. The total area of the melting zone over the Antarctic ice sheet was estimated over 92.5 ± 13.0 x 10^3 km^2 based on the in-situ data collected during the period 1969–1978 (Klokov, 1979). Estimations of the area for the melting zone in Antarctica are also available from the microwave remote sensors for the summers in the period 1979/80– 2005/06; the melting zone has expanded over 25 % of the continent at least five times (Picard et al., 2007).

Remote sensors and geophysical surveys have recently yielded evidence on a large number of glacial lakes in Greenland and Antarctica (Leeson et al., 2015; Arthur et al., 2020). Stokes et al. (2019) used remote sensing data to detect water bodies over the East Antarctic coast, and over 65000 glacial (supraglacial type) lakes were found in the 2017 peak melting season. The total area of these supraglacial lakes is over 1300 km^2, and most of them are located at low elevations. The possible effects of glacial lakes on the global sea level rise are unclear, because the processes and mechanisms driving the meltwater production, accumulation and transport in the glacial hydrological network are not fully understood (Bell et al., 2017; Bell et al., 2019). The glacial lakes are a well-known indicator for climate change (Verleyen et al., 2003; Williamson et al., 2009; Verleyen et al., 2012). Mass loss from the Antarctic ice sheet tripled in 2007–2016 relative to 1997–2006 (Meredith et al., 2019), which may partly explain the observed changes in the physiographic parameters (volume, depth and surface area) for many glacial lakes located in the East Antarctic oases (Levy et al., 2018; Boronina et al., 2020). The glacial lakes are connected by ephemeral streams into a hydrological network that may rapidly develop in the melting season (Lehnherr et al., 2018). The glacial lakes became landlocked after the glaciers retreated. The lakes of the landlocked type occupy local relief depressions over deglaciated areas also named oases in Antarctica (Simonov, 1971; Hodgson, 2012).

Among others, a modelling approach has been applied to understand how climate warming changes the amount of liquid water seasonally formed in the glacial hydrological network, including the lakes and streams. The water balance equation of a lake particularly allows estimating the volume of the lake from known inflow and outflow terms (precipitation, evaporation, surface/subsurface inflow/outflow runoff, water withdrawal) to be measured or modelled. Different processes in Antarctica drive the water exchange in the glacial and landlocked lakes (Simonov, 1971; Krass, 1986; Shevnina and Kourzeneva, 2017). The estimates of the water transport scale for the lakes (and their water budget) are sensitive to uncertainties inherent in the methods applied to evaluate evaporation for both glacial and landlocked lakes (Shevnina et al., 2021). This study suggested the estimations for the uncertainties inherent in the indirect methods applied to simulate the evaporation over the ice-free water table of the glacial lake located in Antarctica.

Performing the direct measurements of evaporation is practically difficult, and various methods are applied ~~to estimations~~ to evaluate various types of ~~the~~ land surface, including ~~the~~ lakes. ~~The~~ methods are generally indirect, because they are like narrow or “pointed” measurements made by an instrument, and/or the evaporation is calculated from measured meteorological variables (Guidelines, 2008). Many of these methods require special instruments and sensors for humidity, wind speed and temperature (Brutsaert, 1982; Finch and Hall, 2001): the turbulence measurements (i.e., the EC method), profile measurements (i.e., the aerodynamic methods) and the measurements at various heights (i.e., Bowen-ratio based energy-balance methods). Among others, the eddy covariance (EC) method is recognized as the most accurate in estimations of the evaporation. This method has been used for more than 30 years (Stannard and Rosenberry, 1991; Blanken et al., 2000; Aubinet et al., 2012). The turbulence (EC) measurements are direct measurements of the vertical flux of water vapour occurring over the lake surface. Assuming that the flux at the measurement height is the same as at the surface (or low as in our field experiment), the EC measurements are direct measurements of local evaporation over the lake. We assumed in this study that the point measurement of the EC measuring system was a direct measurement of the lake evaporation. The Dalton type semi-empirical equations allowed us to calculate the evaporation from the meteorological observations collected at the monitoring sites (Braslavskiy, 1966; Keijman, 1974; Sene et al., 1991; Shuttleworth, 1993; Majidi et al., 2015). The empirical coefficients in these equations should only be used on the conditions they were determined for (Finch and Hall, 2001). Estimates of the evaporation (or sublimation) over the Antarctic areas demonstrate a huge variation range (Thiery et al., 2012). The evaporation over the lakes located in Antarctica are evaluated with the semi-empirical equation with the coefficients estimated for different climate zones (Borghini et al., 2013; Shevnina and Kourzeneva, 2017). In this study, we estimated the uncertainties in the Dalton-type equations applied to calculate evaporation over the lakes located in Antarctica.

This study addresses summertime evaporation over the ice-free water surface of a glacial lake evaluated by applying various methods, namely, the eddy covariance, the bulk-aerodynamic and Dalton type semi-empirical equations. The EC measurements are used as a reference to evaluate the uncertainties in the estimates with the bulk aerodynamic method and the semi-empirical equations. This information is beneficial, because EC measurements over glacial lakes are rarely available, and other estimates must be used. The EC measurements of evaporation were collected during a field experiment on the glacial Lake Zub/Priyadarshini located in the Schirmacher oasis, East Antarctica. We also suggested ~~the~~ empirical relationship from the daily series of evaporation estimated after applying the direct EC method and measurements at the nearest meteorological site.

2 The study area, weather and lakes

The Schirmacher oasis (70° 45′ 30″ S, 11° 38′ 40″ E) is located approximately 80 km from the coast of the Lazarev Sea, Queen Maud Land, East Antarctica. The oasis is the ice-free area elongated in a narrow strip around 17 km long and 3 km wide in West–Northwest to East–North-East (Fig. 1 b); its total area is 21 km^2 (Konovalov, 1962). The relief is hillocks with absolute heights up to 228 m above sea level. The oasis separates the continental ice sheet from the ice shelf, and the region allows studies on deglaciation processes and the continental ice sheet mass balance components, including melting and liquid water runoff (Klokov, 1979; Srivastava et al., 2012).

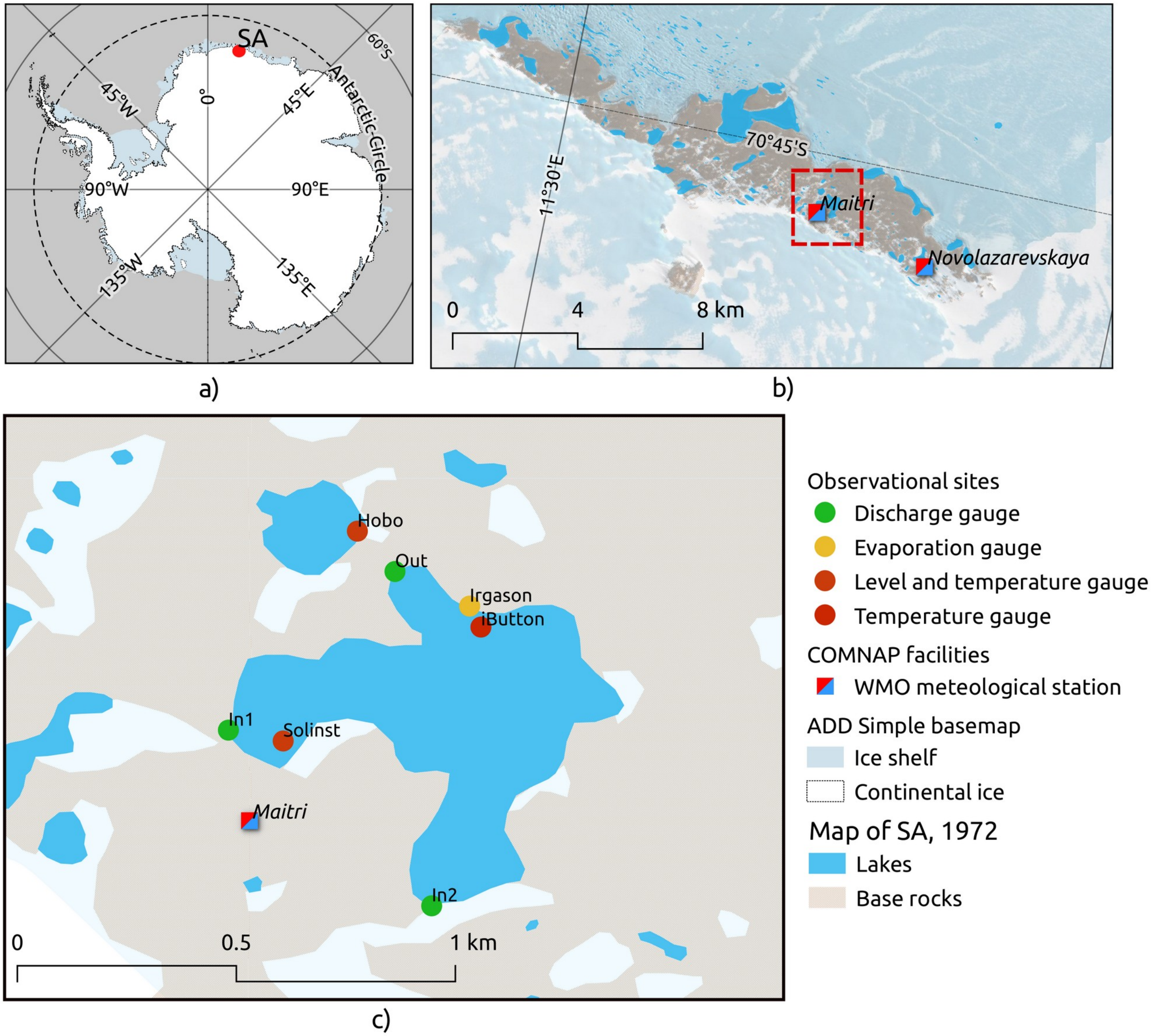


Figure 1. The lakes in the study region: (a) Location of the Schirmacher oasis (SA) in Antarctica; (b) the lakes in SA (after Map of SA, 1972) with Landsat Image Mosaic of Antarctica, LIMA given as the background; (c) the temporal observational network in the catchement of Lake Zub/Priyadarshini.

The climate of the Schirmacher oasis is characterized by low air humidity and temperature and a persistent (katabatic) wind blowing most of the year. This easterly-southeasterly wind blows from the continental ice sheet, and advects cold continental air masses to the oasis (Bormann and Fritzsche, 1995). Two meteorological sites operate in the Schirmacher oasis. The observations were started in 1961 at the Novolazarevskaya (Novo) meteorological site (70°46′36″S, 11°49′21″ E, 119 m asl, World Meteorological Organization (WMO) number 89512). The Maitri meteorological site (70°46′00″S, 11°43′53″ E, 137 m asl, WMO number 89514) opened in 1989 and is located over 5.5 km from the Novo site. Both meteorological sites are included in a long-term monitoring network; their measurements are performed according to standards of WMO (Turner and Pendlebury 2004). Table 1 shows weather conditions during the austral summer 2017–2018 and averaged over the period 1961–2020 according to the observations at the Novo site (the data are provided by the Arctic and Antarctic Research Institute at http://www.aari.aq/default_ru.html, last access 03.06.2021).

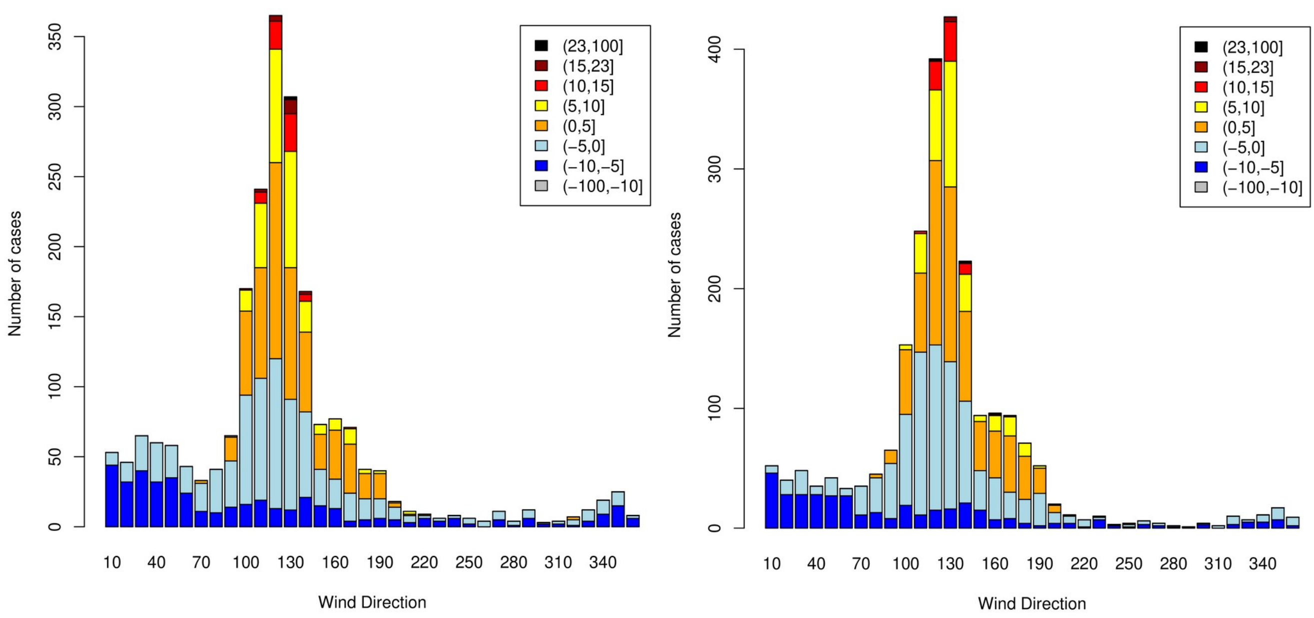
Table 1. Basic statistical characteristics for the meteorological parameters observed in the summer months for the period 1961–2020 and 2017–2018 (based on the observations at Novo site).

Parameter	Period	December	January	February
Air temperature, °C	1961–2020	–3.9 / –1.0 /1.5*	–2.5 / –0.4 / 1.4	–4.7 / –3.3 / –1.0
	2017	–0.1	–	–
	2018	–	–1.3	–3.0
Relative Humidity,%	1961–2020	47 / 56 / 69	49 / 56 /66	41 / 49 / 59
	2017	50	–	–
	2018	–	57	49
Atmospheric pressure, Pa	1961–2020	974.7	975.6	973.3
	2017	960.3 / 970.2 / 986.2	–	–
	2018	–	954.5 / 969.9 / 987.0	954.7 / 966.6 / 977.3
Wind speed, ms^{-1}	1961–2020	4.3 / 7.4 / 10.3	3.1 / 7.0 / 10.4	5.8 / 9.4 / 13.1
	2017	7.0	–	–
	2018	–	6.2	9.4
Soil surface temperature, ºC	1961–2020	3.0 / 6.7 / 10.0	3.0 / 6.7 /11.0	–2.0 / 0.2 / 4.0
	2017	5.0	–	–
	2018	–	3.0	0.0
Precipitation, mm	1961–2020	0.0 / 5.3 / 54.8	0.0 / 2.6 / 38.0	0.0 / 2.9 / 25.9
	2017	1.9	–	–
	2018	–	10.9	4.6

*Min / Mean / Max

The field experiment lasted 38 days in January–February 2018. The weather during the experiment was colder and less windy, while the precipitation and relative humidity were close to the long-term mean values (Table 1). According to the Novo meteorological site, the daily air temperatures ranged from –8.3 to 2.8 ºC, and the wind ranged speed from 1.5 to 14.3 ms^{-1}, with an average of 6.2 ms^{-1}. The observations at the Maitri site were very similar to those at the Novo site, with the correlation coefficient between the daily series of the air temperature, relative humidity and wind speed varying from 0.95 to 0.98. According to the Maitri meteorological site, the wind speed varied from 1.6 to 14.4 ms^{-1}, with an average of 6.7 ms^{-1}. The air temperature ranged from –8.3 to 2.1 ºC, with an average of 1.5 ºC. The average relative humidity during the summer was 54 %.

To plan the field experiment, we used 6-hour synoptic observations at the Novo site available from the British Antarctic Survey Dataset (https://www.bas.ac.uk, last accessed 14.12.2018) covering the period 1998–2016 to calculate the wind direction and frequency of wind speed anomalies over the multi-year means for eight ranges (Fig. 2). The positive anomalies in the wind speed suggest that the observed wind speed is higher than the mean value. The prevailing wind direction generally ranged from 120 to 140º (Fig. 2); the positive wind speed anomalies are typical for this range, i.e., one can expect the majority of strong winds from these directions. We accounted for these circumstances by choosing the location to deploy the EC measuring systems, to aim the water vapor sensor, and to design its maintenance system to sustain the local winds during the field experiment.



a) b)

Figure 2: Wind direction (x-axis) and frequency of wind speed anomalies (y-axis) according to the observations at the Novo meteorological site: (a) December; (b) January.

More than 300 lakes are mapped in the oasis (Fig. 1 b), and many of the lakes are ice free in summertime for almost two months (Kaup et al., 1988; Richter and Borman, 1995; Kaup et al., 1995; Kaup, 2005; Khare et al., 2008; Phartiyal et al., 2011). The physiography of the lakes is available from bathymetric surveys for only the largest lakes (Simonov and Fedotov, 1964; Loopman et al., 1988). The hydrological cycle and changes in the volume in these lakes are modulated by the seasonal weather cycle (Sokratova, 2011; Asthana et al., 2019).

This study focuses on Lake Zub/Priyadarshini, which is among the largest and warmest water bodies of the Schirmacher oasis. Water in the lake is mainly sourced by the continuous glacial melting water (Gopinath et al., 2020). The lake has not fully lost the connection to the glacier, ~~and its~~ melting is still a major inflow term of the lake's water budget. ~~It~~ allows us to suppose that Zub/Priyadarshini is ~~the~~ glacial type (not ~~the~~ landlocked type as given in Phartiyal et al., 2011). This lake is the lowest in the glacial lakes chain over the continental ice sheet. The lake catchment includes a low portion of glaciated area that results in a specific thermal regime and lake water budget. The lake's water temperature rises up to 8–10 ºC in January (Ingole and Parulekar, 1990), which is typical for the landlocked lakes (Simonov, 1971).

The lake's surface area is 33.9 x10^3 m^2, its volume is over 10.0 x10^3 m^3, and the lake's maximal depth is 6 meters (Khare et al., 2008). Lake Zub/Priyadarshini occupies a local depression that is fed by two inflow streams present during the warm seasons. The outflow from the lake occurs via a single stream. The lake stays ice free for almost two summer months from mid-December to mid-February, and it has no significant thermal stratification during this period (Sinha and Chatterjee, 2000). The lake is used as the water supply of the year-round scientific Indian base Maitri (Dhote et al., 2021).

3. Data and Methods

3.1 Data

We collected the hydrological and ~~special~~ meteorological observations needed to evaluate the water balance terms of Lake Zub/Priyadarshini in the field experiment of 2017–2018. The temporal hydrological network included water level/temperature gauges, water discharge/level gauges and an evaporation gauge (Fig. 1 c). This study used only those data required to evaluate ~~only~~ one term of a lake's water budget, namely, the evaporation. The evaporation gauge was a flux tower equipped with the Irgason EC measurement device by Campbell Scientific (user manual available at https://s.campbellsci.com/documents/ca/manuals/irgason_man.pdf, last access 09.07.2021). The Irgason comprises a 3D sonic anemometer and two gas analyzers measuring CO2 and H2O concentrations. It was deployed on the shore of the lake to collect high-frequency data on the wind speed/direction and water vapor concentration needed to evaluate the evaporation with the EC method. The flux tower was placed 5–6 m from the shoreline of Lake Zub/Priyadarshini for the period 1 January to 7 February, 2018 (Shevnina, 2019). Irgason was deployed on the boom at the height of 2 meter and was fixed with 6 metal guidelines angled 120° to each other (Fig. 3 a). The field experiment lasted ~~for~~ 38 days, and the meteorological parameters (air temperature, wind speed and relative humidity) were measured simultaneously at the Maitri meteo site and at the evaporation gauge located on the lake shore (Irgason in Fig. 1 c). The data gathered by the various sensors cover observational periods lasting from 14 to 45 days (Table 2).

Table 2. Hydrological and meteorological data collected during the field experiment during the 2017–2018 summer.

Site / Sensor (Fig. 1 c)	Elevation, m	Measured variables	Period	Time series used in the analysis
Irgason site	125.5	Air temperature, ºC; H2O concentration, g/m^3; 3D wind speed, ms^{-1}	01.01.2018 – 07.02.2018	30 minute
Hobo	123	Water temperature, ºC	30.12.2017 – 09.02.2018	Daily average
Solinst	119.5	–	01.01.2018 – 15.12.2018	
iButton	123	–	27.01.2018 – 09.02.2018	
Maitri site	137.5*	Air temperature, ºC; relative humidity, %; wind speed, ms^{-1}	01.12.2017 – 28.02.2018	Daily average

* measured during the summer season 2017–2018 by the geogesic instrument Leica CS10; the elevation is given in WGS84 vertical datum.

The footprint is an important concept for evaluating the fluxes correctly for the EC method. The footprint is defined by a sector of wind direction covering the source area: The footprint length depends on the sensors’ height (Kljun et al., 2004; Burba et al., 2016). The location of the Igrason accounted for the prevailing wind directions (Fig. 2), so that for most of the time the wind is blowing from the source area covered by the lake surface. We filtered out data outside the footprint (Fig. 3 b). The gaps in the wind direction were replaced with average values of the neighbouring 30-minute blocks. The Irgason was settled at the height of 2 meters above the ground, which allows for footprint lengths of less than 200 meters (Fig. 3 c). This distance is less than twice those between the Irgason and the shore of Lake Zub/Priyadarshini in an east-southeast direction (Fig. 1 c). This condition ensures that the retained data is representative only from the lake and free of contamination from the shores. The Irgason’s height allows for a blind zone near the tower; therefore, the stones on the lake shore do not affect the fluxes. The Irgason’s raw data consisted of the values measured at a frequency of 10 Hz. We used these raw data to calculate a 30-minute series of the evaporation, turbulent fluxes of momentum, sensible heat and latent heat, as well as air temperature, wind speed, and wind direction. The daily evaporations were calculated as a sum of the 30-minute series, and the combination of the EC footprint and the small dimension of the lake allowed us to consider these measurements as direct measurements of the evaporation over the lake surface.

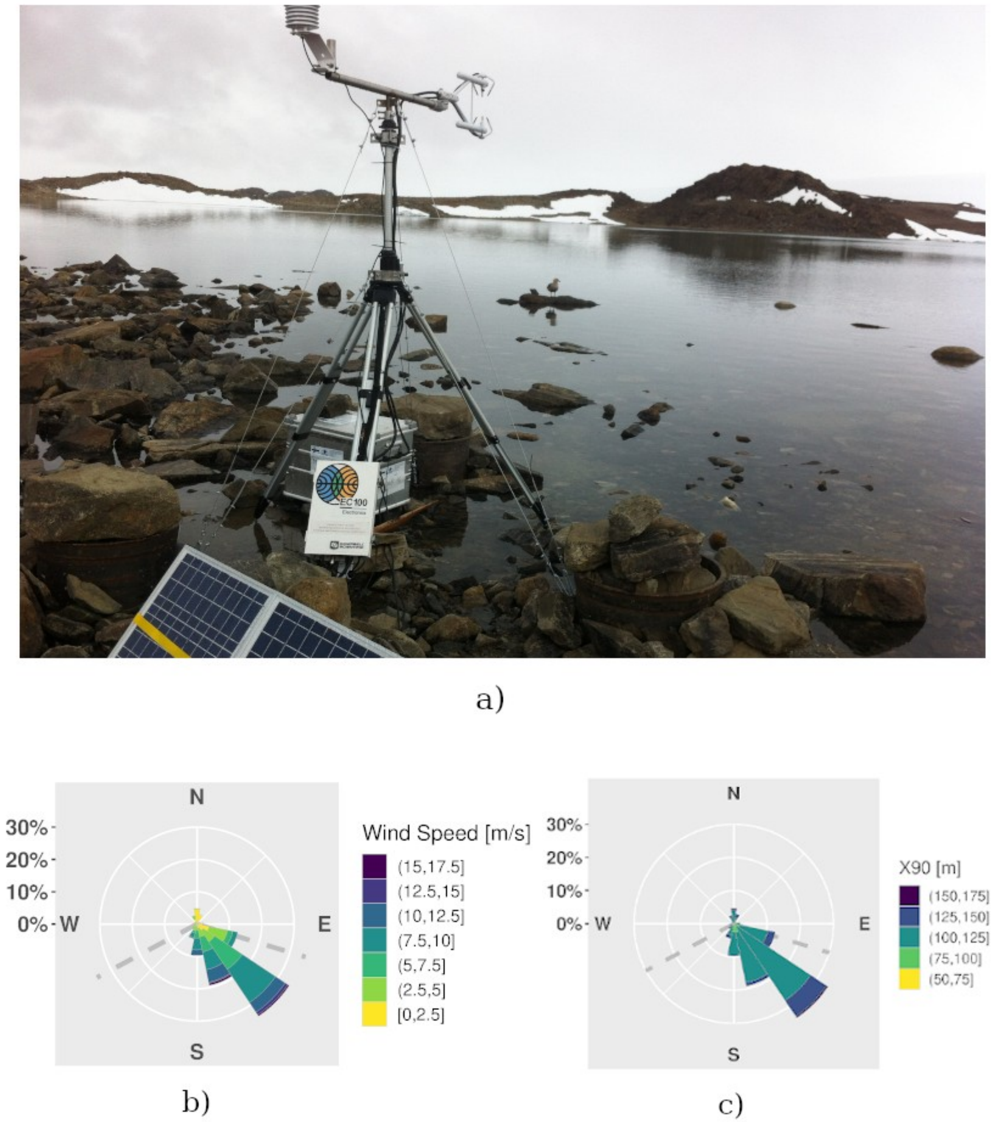
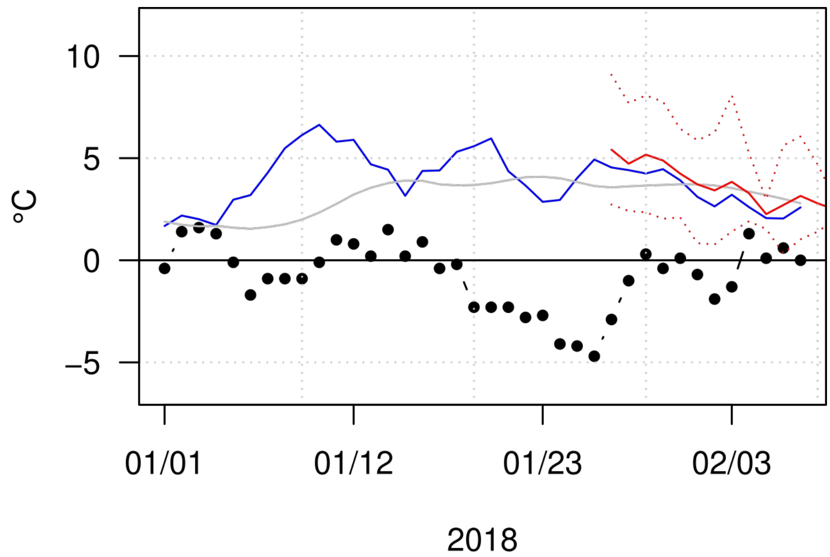


Figure 3: The experiment on the coast of Lake Zub/Priyadarshini: (a) Irgason deployed on the lake shore (06.01.2018); (b) wind speed and direction measured at the Irgason site, the dashed line indicates the footprint wind sector; (c) the footprint length estimate (X90).

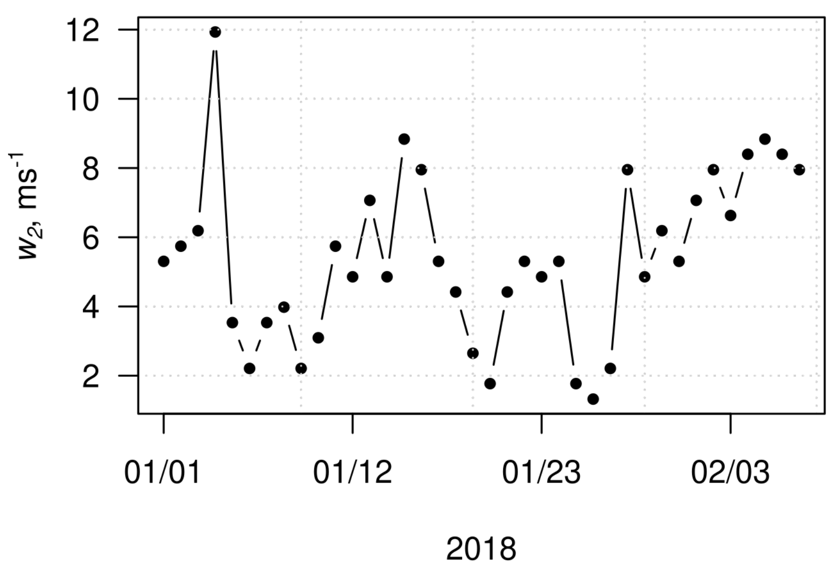
The measurements of the water temperature were needed to allow the estimation of the evaporation after the Dalton type empirical equations. Therefore, we measured the water temperature over the surface of the lake with three sensors installed in Lake Zub/Priyadarshini (Fig. 1 c) at the depths of 0.2 meters (Hobo, iButton) and 3.9 meters (Solinst). The sensors

Solinst, Hobo and iButonts were installed at different depths, which was the result of a misunderstanding between the hydrologists working in the field. We expected that the water temperature in the lake was measured by a chain of sensors instead of the Solinst. The Hobo sensor was deployed on the stream inletting the neighbouring lake, whose measurements were considered to be representative for the water level and the stream's water temperature more than for the neighbouring lake itself. We assumed that Lake Priyadarshini was thermally homogeneous down to the bottom (Sinha and Chatterjee, 2000). Thermal homogeneity during the summers is typical for the lakes of a similar morphology that are located in the Larsemann Hills oasis, East Antarctica (Shevnina and Kourzeneva, 2017). The lake surface temperature was measured every 10 minutes, and we further calculated the daily average series of the lake's water temperature. Two temperature sensors (Solinst and Hobo) also measured the barometric pressure, allowing us to evaluate the water level/stage in Lake Zub/Priyadarshini; however, we did not utilize ~~these~~ data in this study, which focused only on evaporation.

Figure 4 a shows the daily time series of the lake water temperature, air temperature and wind speed calculated from the measurements the sensors performed during the period of the experiment. The best agreement was found for the water temperature measured by the sensors Hobo and iButton; the correlation coefficient for these series equals 0.89. The water temperature measured by the Solinst sensor is systematically lower than those measured by the Hobo and iButton (Fig. 4 a). This circumstance is likely connected to the effect of the cold water incoming with the inflow stream, which is incoming close to the deployment location of the Solinst temperature sensor. This inflow stream results from the small glacial lake located upstream of Lake Zub/Priyadarshini. The water in the upstream lake is colder than in Lake Zub/Priyadarshini itself.



(a)



(b)

Figure 4: Daily time series of: (a) the lake surface water temperature measured by the Hobo (blue), iButton (red) and Solinst (grey), and the air temperature measured at the Maitri site (black); (b) the 2-meter wind speed estimated with

the logarithmic profile after the measurements at Maitri site. The red dotted lines show the daily minimum and maximum water temperatures measured by the iButton temperature sensor.

We applied the data collected by the meteorological sensors installed at both the Maitri and Irgason sites in our calculations after applying the Dalton-type equations. The meteorological sensors are installed at different heights: ~~T~~he Irgason's sensors are deployed at a height of 2 meters over the ground (the lake water table), and the Maitri site's sensors are mounted on the mast at a height of 6 meters over the ground. It requires applying the transformation to the wind speed measured at the Maitri site before using these measurements in the Dalton-type equations. ~~Furthermore, we~~ used the logarithmic approximation of the wind profile to correct the wind speed data measured at the Maitri site, where the roughness length constant equals 0.0024 meters (as suggested: https://wind-data.ch/tools/profile.php?lng=en, last access 15.10.2021). We did not use any transformation for the data on the relative humidity and air temperature, because their changes with elevation are negligible in our case (Tomasi et al., 2004).

3.2 Methods

The daily evaporation over the ice-free surface of Lake Zub/Priyadarshini was evaluated with both direct and indirect methods. The indirect methods are the bulk-aerodynamic method and Dalton type semi-empirical equations. We used the data collected by the Irgason instrument installed on the shore of Lake Zub/Priyadarshini to evaluate the evaporation with the direct EC method. The Irgason raw data were measured with a frequency of 10 Hz and required postprocessing. We followed Potes et al. (2017) in the postprocessing procedure of the raw data, which were further filtered in three steps: ~~I~~n the first step, the bad data with less than 50 % of total 10 Hz measurements were excluded; in the second step, we excluded all data automatically flagged for low quality along with the data with a gas signal strength of less than 0.7 (or 70 % of the strength of a perfect signal). The gas signal strength is usually lower than 0.7 during rain, which is not observed in Antarctica. The raw data were processed in the third step to remove spikes after applying the Vickers and Mahrt (1997) method. This procedure was repeated up to 20 times or until no more spikes were found. Finally, the 30-minute values were obtained of the atmospheric fluxes (the momentum flux, the sensible heat flux, the latent heat flux), the water vapor concentration, the specific humidity, various turbulence parameters and evaporation (see the Supplement).

We also filtered the data outside the footprint, which covered the winds with the direction ranging from 105 to 240º (Fig. 3 b), to account only for those values collected within the lake surface area. We excluded 18 % of the total measurements from further consideration after three filtering steps, and these gaps were replaced with the median and median values. Finally, the daily evaporation over the lake surface was estimated as the sum of the 30-minute values in each day of the experimental period. We also evaluated the relative humidity from the water vapor concentration as given by Hoeltgebaum et al. (2020) to compare with the relative humidity measured at the Maitri site.

Uncertainties in the estimation of evaporation after applying any method include the instrumental errors associated with the specific instrument. Aubinet et al. (2012) suggest three methods that allow us to quantify the uncertainty of the EC method. We applied the paired tower method in this study to evaluate the instrumental uncertainties of the EC method by taking advantage of an intercomparison campaign in the Alqueva reservoir, Portugal, in October 2018. The instrumental error does not depend on the region where the instrument will be used; therefore, the intercomparison may be performed elsewhere. The relative instrumental error estimated in this intercomparison campaign was 7 % (see the Annex). The EC method's uncertainties also include the errors due to the filtering of measurements within the footprint area. In our study, 18 % of the gaps were filtered, and we filled these data with the mean and median values. The large number of filters and corrections that we applied to the EC data allowed us to reduce the errors and uncertainties. Even the EC method itself has some errors and uncertainties, but it is the most versatile and accurate method to measure the evaporation.

The evaporation (kg m^{-2} s^{-1}) is defined in the bulk-aerodynamic method as the vertical surface flux of water vapor due to atmospheric turbulent transport. It is calculated from the difference in specific humidity between the surface (i.e., ice or water) and the air, as well as the factors that affect the intensity of the turbulent exchange: wind speed, surface roughness, and thermal stratification (Boisvert et al., 2020; Brutsaert, 1985). In our study, the evaporation was calculated as follows after the bulk-aerodynamic method:

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

where, E is the evaporation (kg s^{-1}); ρ is the air density, C_{Ez} is the turbulent transfer coefficient for moisture, q_S is the saturation specific humidity corresponding to the lake surface temperature, q_{az} is the air specific humidity, and w is the wind speed. The subscript z refers to the observation height (here 2 meters). We applied the value of 0.00107 based on measurements over a boreal lake (Heikinheimo et al., 1999; Venäläinen et al., 1998) for the turbulent transfer coefficient for moisture under neutral stratification (C_{EzN}). This allows us to better take into account the different regime of turbulent mixing over a small lake compared to the sea (Sahlee et al., 2014). The stratification is not always neutral, so we took into account the effects of stratification on the turbulent transfer coefficient C_{Ez} as follows:

$$C_{Ez} = \frac{C_{DzN}^{1/2} C_{EzN}^{1/2}}{\left[1 - \left(\frac{C_{DzN}^{1/2}}{k} \right) \psi_m \left(\frac{z}{L} \right) \right] \left[1 - \left(\frac{C_{EzN}^{1/2}}{k} \psi_q \left(\frac{z}{L} \right) \right) \right]} \tag{2}$$

where C_{DzN} is the neutral drag coefficient for the lake surface (0.00181; Heikinheimo et al. (1999)), k is the von Karman constant (0.4), and the effects of thermal stratification are presented by the empirical functions (ψ_m and ψ_m) depending on the Obukhov length (L). For ψ_m and ψ_q, we used the classic form by Businger et al. (1971) for unstable stratification and that of Holtslag and de Bruin (1988) for stable stratification. The values by Heikinheimo et al. (1999) were given for z = 3 meters, and converted to our observation height of 2 meters using Launiainen and Vihma (1990), and the same algorithm was applied to iteratively solve the interdependency of the turbulent fluxes and *L*. The latent heat flux is obtained by multiplying the evaporation rate by the latent heat of vaporizations.

The Dalton type semi-empirical equations allow calculation of the evaporation from a wind function and a gradient of the temperature of water surface and ambient air measured at 2 meters height:

$$E = C(e_s - e_2) \quad (3)$$

where, E is daily evaporation, mm day^{-1}; e_s is the water vapor saturation pressure; e_2 is the water vapor pressure at 2 meters height; C is a coefficient (or a function) depending on meteorological conditions (or a linear wind function with two parameters that compute boundary layer transfer coefficients (Tanny et al., 2008)). The C is evaluated from observations with empirical approximations (Finch and Hall, 2001).

We applied three semi-empirical equations in this study to calculate the daily evaporation rate suggested by Penman (1948), Doorenbos and Pruitt (1975) and Odrova (1979), Eqs. 4 – 6, respectively:

$$E = 0.26(1+0.54\,w_2)(e_s - e_2) \quad (4)$$

$$E = 0.26(1+0.86\,w_2)(e_s - e_2) \quad (5)$$

$$E = 0.14(1+0.72\,w_2)(e_s - e_2) \quad (6)$$

where E is the evaporation expressed in mm day^{-1}; w is the wind speed measured at the 2 meters height; e_s and e_2 are water and air vapor saturation pressure, given in millibars (calculated according to the Tetens's formula in Stull, 2017). The approximations by Penman (1948) and Doorenbos and Pruitt (1975) are among the most often-used methods in hydrological practice (Finch and Hall, 2001); therefore, we have chosen them in this study. The method by Odrova (1979) is used to evaluate the daily evaporation over the lakes in Antarctica; however, the scope of uncertainties of this method has not been previously estimated (Shevnina and Kourzeneva, 2017). We calculated the daily evaporation separately after applying the semi-empirical equations by using the meteorological observations collected at the Maitri site and at the lake shore (Igrason site). The daily series of the evaporation were evaluated after applying the bulk-aerodynamic method from the 30-minute series of the meteorological data collected at both sites.

The empirical coefficients in the Dalton type equations usually limit their applicability to the region where such coefficients are obtained (Finch and Hall, 2005). The empirical coefficients in the equations (4-6) are evaluated from the data gathered in regions with different climates; therefore, they probably will not be applicable for Antarctica lakes. We suggested in this study ~~the~~ regional empirical relationship by using the daily series of the evaporation estimated after applying the direct EC method and observations at the meteorological site nearest to the lake. The evaporation (mm day^{-1}) was evaluated with the linear regression model $a + b_1 w_2 + b_2 (e_s - e_2)$, where $(e_s - e_2)$ is expressed in mbar. The efficiency of the relationship was estimated with the cross validation procedure, in which the whole period with observations (38 days) was divided into two subperiods of 19 days each. The daily evaporations within the first period were used to estimate the empirical coefficients; then, the daily evaporation in the second period were used as the independent data while estimating the efficiency of the empirical relationship. The procedure was then applied vice-versa: that is, the values for the empirical coefficients were evaluated from the evaporation over the second subperiod, and the efficiency of the relationship was estimated using the evaporation in the first subperiod.

The evaporation after applying the indirect methods were compared to those calculated using the direct (EC) method to find the method with the lowest range in the uncertainties. We used the Pearson correlation coefficient and the Nash-Sutcliffe efficiency index (Nash and Sutcliffe, 1970) as given by Tanny et al. (2008) to estimate the efficiency of the bulk-aerodynamic method and semi-empirical equations:

$$NSS = 1 - \sqrt{\frac{\sum_{i=1}^{n}\left(E_{EC}^{i} - E_{m}^{i}\right)^2}{\sum_{i=1}^{n}\left(E_{EC}^{i} - \bar{E}_{EC}\right)^2}} \quad , \tag{7}$$

where E_{EC} and E_m are the evaporation estimates after the direct method and after the indirect method, respectively; $\bar{E}_{EC}$ is an average daily evaporation over the observational period (i.e., 38 days). The values of the NSS can range from $-\infty$ to 1, and NSS = 1 indicates a perfect match of the data modelled after the indirect methods to the data modelled after the EC method; NSS = 0 indicates that the indirect methods are as accurate as the average of the EC data.

We also applied the s/σ criteria after Popov (1979):

$$s = \sqrt{\frac{\sum_{i=1}^{n}\left(E_{EC}^{i} - E_{m}^{i}\right)^2}{(n-m)}} \quad , \tag{8}$$

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}\left(E_{EC}^{i} - \bar{E}_{EC}\right)^2}{n}} \quad , \tag{9}$$

where E_{EC} and E_m are the evaporation estimates after the direct method and after the indirect method, respectively, n is the length of the series, and m=2 (a number of the empirical coefficients in the empirical relationship). A criterion value less than 0.8 shows that the indirect method is acceptable for estimations of the evaporation against the EC method.

The study's region is featured with the persistent katabatic winds blowing from the continental interior. Fig. 3 b shows that almost all winds come from a direction that would be the direction of katabatic winds. However, it is not guaranteed that all these winds are entirely of katabatic origin: Some may be driven by a combined effect of katabatic and synoptic forcing.

4 Results

4.1 Evaporation

We considered the direct EC method the most accurate, providing the reference estimates for the daily evaporation over the lake surface (Finch and Hall, 2005; Tanny et al., 2008; Rodrigues et al., 2020). According to the EC method, the daily evaporation varied from 1.5 to 5.0 mm day^{-1} with the average equals to 3.0 mm day^{-1}; the standard deviation is ± 1.1 mm day^{-1}. The average was calculated dividing 114 mm of evaporated water (the sum of the 30-minute series of evaporation) by the number of days in the observational period (38). We used two methods in this study to fill the 18 % gap in the 30-minute series: ~~B~~y the median and mean values, however, the results differ by only 2 mm. Therefore, we decided to only use the median value to fill whole gaps in the 30-minute series of the evaporation. The sum of the evaporation over the period of the field experiment is 94 mm if we simply excluded whole gaps in the 30-minute series.

We estimated the uncertainties inherent in the indirect methods by comparing their results with those based on the EC method. The bulk-aerodynamic method suggests the average daily evaporation to be 2.0 mm day^{-1}, which is over 32 % less than the result based on the EC method. This is the best estimate for the average daily evaporation among the other indirect methods (bold notation in Table 4). All the Dalton type semi-empirical equations underestimated the evaporation over the lake surface by over 40–72 %, and the method after Odrova (1979) yielded the maximal underestimation of the mean daily evaporation over the lake surface. The uncertainties in the estimates after the indirect methods are approximately the same for both cases of the input data (Maitri and Irgason).

Table 4. The daily evaporation (mm day^{-1}) calculated after applying the indirect methods for the experiment on Lake Zub/Priyadarshini for the period of 38 days of the field experiment (01.01.2018 – 07.02.2018).

Methods	Input data: Irgason site				Input data: Maitri site			
	Min/Max	Mean ± *SD**	Sum	k^{**}	Min/Max	Mean ± *SD*	Sum	k
Bulk-aerodynamic method	**0.6 / 3.5**	**2.0 ± 0.8**	**78**	**1.5**	**0.7 / 2.9**	**1.9 ± 0.6**	**72**	**1.6**
Penman, 1948	0.0 / 2.0	1.3 ± 0.5	48	1.9	0.1 / 2.2	1.2 ± 0.5	46	2.0
Doorenbos and Pruitt, 1975	0.0 / 2.9	1.8 ± 0.8	68	1.4	0.2 / 3.2	1.7 ± 0.7	66	1.4
Odrova 1979	0.1 / 1.3	0.8 ± 0.3	32	2.9	0.1 / 1.6	0.8 ± 0.3	32	2.9

* *SD* is the standard deviation; ** k is ratio E_{EC}/E_m, where E_{EC} and E_m are the evaporation estimates after the direct method and after the indirect method, respectively.

Figure 5 shows the daily evaporation estimated after using the direct EC method against those estimated after applying the indirect methods calculated applying the meteorological observations collected at the Maitri and Irgason measurement sites. There is not a big difference in the results; therefore, we can recommend using the meteorological observations gathered by the nearest site to further estimate the evaporation. The efficiency of the indirect methods to model the day-by-day series of the evaporation was quantified by applying the Pearson correlation coefficient (*R*), the Nash-Sutcliffe index (*NSI*) and the s/σ criteria (*SSC*). Table 5 shows the values of these criteria.

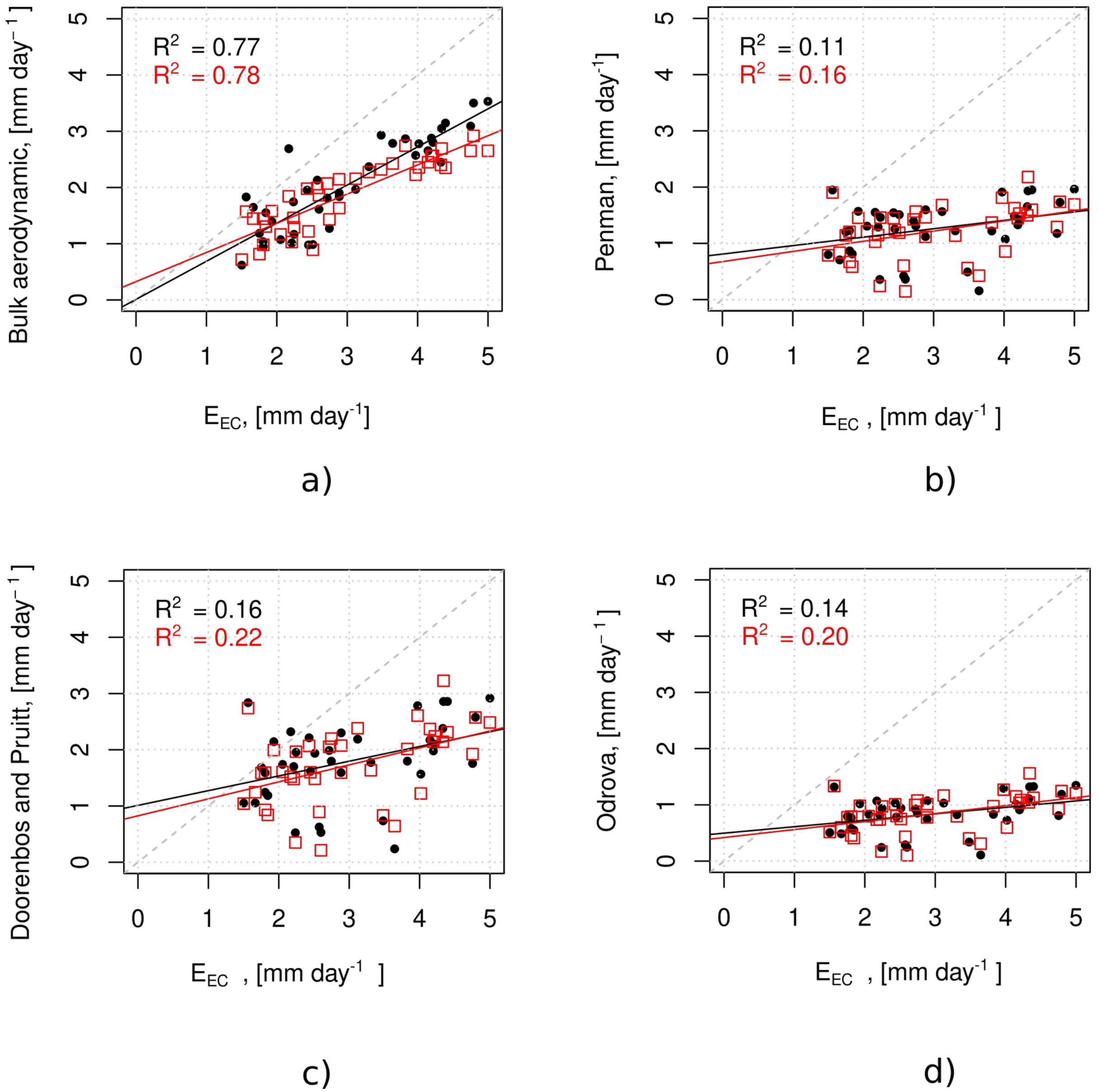


Figure 5: Scatter plots of the daily evaporation estimated with the indirect methods (Y-axis) against the direct EC method (X-axis): (a) the bulk-aerodynamic; (b) Penman; (c) Doorenbos and Pruitt; (d) Odrova. The red dots indicate the estimates of the evaporation with the meteorological parameters measured at WMO synoptic site Maitri, which is the nearest to Lake Zub/Priyadarshini. The black dots indicate those estimates of the evaporation performed with the meteorological parameters measured at the lake shore (Irgasin site).

The bulk-aerodynamic method gave the best fit to the EC method according to all criteria (bold notation in Table 5). As one can expect, the efficiency of the Dalton type semi-empirical equations is poor: The correlation coefficient varied from 0.12 to 0.34, and both *NSS* and *SSC* criteria indicated a low ability of the methods to estimate the daily evaporation.

Table 5. The efficiency of the indirect methods with the Pearson correlation coefficient (*R*), the Nash-Sutcliffe index (*NSI*) and s-sigma criteria (*SSC*).

Methods	Input data: Irgason site			Input data: Maitri site		
	R	*NSI*	*SSC*	*R*	*NSI*	*SSC*
Bulk-aerodynamic	**0.87**	**–0.1**	**1.1**	**0.88**	**–0.5**	**1.2**
Penman, 1948	0.33	–2.7	2.0	0.41	–2.8	2.0
Doorenbos and Pruitt, 1975	0.40	–1.3	3.3	0.46	–1.3	3.3
Odrova 1979	0.37	–4.2	2.3	0.45	–4.1	2.3

The bulk-aerodynamic method also allows the best estimates for the day-by-day series of the evaporation (Table 5); however, even this method cannot be suggested to evaluate the daily evaporation using the meteorological observations at the Maitri site (Fig. 6). The mean difference between the daily evaporation estimated after the EC and bulk-aerodynamic method is 0.6 mm day^{-1}, and it takes the maximum number of days with wind speeds of 6–7 m s^{-1} (Fig. 6 and Fig. 4 b).

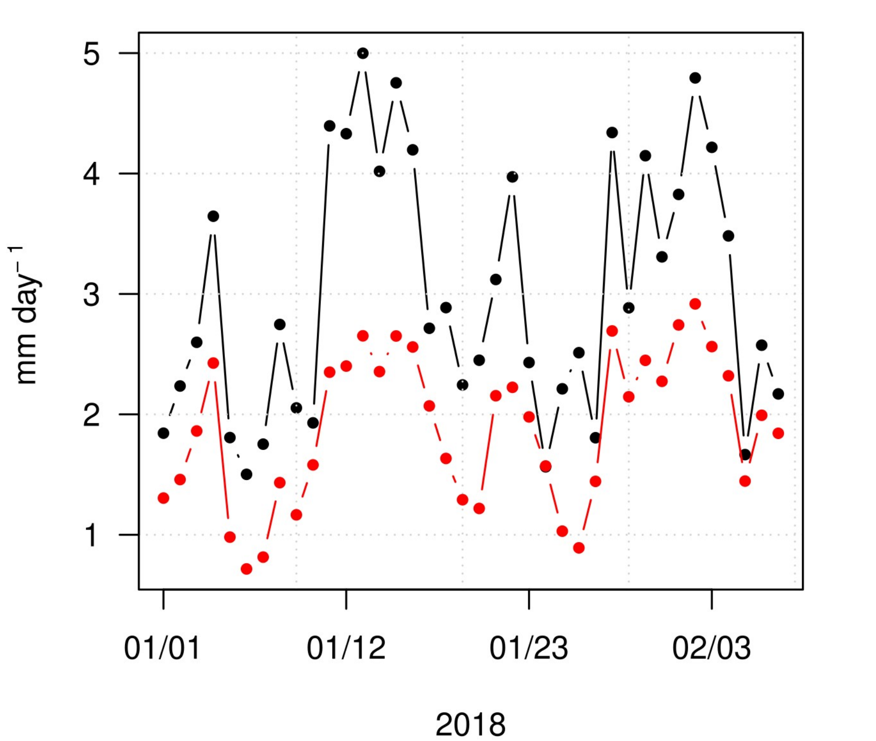


Figure 6. The daily time series of evaporation (mm day^{-1}) calculated after the direct EC method (black) and the indirect bulk-aerodynamic method by applying the meteorological measurements at the Maitri site (red).

4.2 Empirical models

The empirical coefficients limit applications of the Dalton type equations to regions where these coefficients are obtained, and no suggestions are given for Antarctica (Finch and Hall, 2001). We further suggested using ~~the~~ regional empirical relationship to apply the data to the daily evaporation estimate after <using? applying?> the direct EC method and collecting observations at the meteorological site nearest the lake. The evaporation (mm day^{-1}) was evaluated with the linear regression model $a + b_1 w_2 + b_2 \left(e_s - e_2\right)$, where $\left(e_s - e_2\right)$ is expressed in mbar. We estimated the empirical coefficients ~~in~~ this relationship based on whole observations ~~as well as on~~ two subsets collected in two periods. Verification with independent observations is needed to evaluate how effective the empirical relationship is in simulating observations. It was not possible to fully estimate the quality of the model because no independent evaporation measurements were ~~in rest~~ in the case of using whole observations in the fitting of the empirical coefficients. ~~Therefore, the~~ verification of the fitted regression models was performed by applying ~~the~~ cross validation procedure: ~~T~~he empirical coefficients were estimated with the data collected during the period of 01.01.2018–19.01.2018 (19 days), and this linear regression was applied to simulate the daily evaporation for the period of 20.01.2018–07.02.2018 (Fig. 7). The procedure was then repeated in reverse: ~~T~~he linear regression was evaluated from the data collected over the period of 20.01.2018–07.02.2018, and it was used to model the daily evaporation for the period of 01.01.2018–19.01.2018.

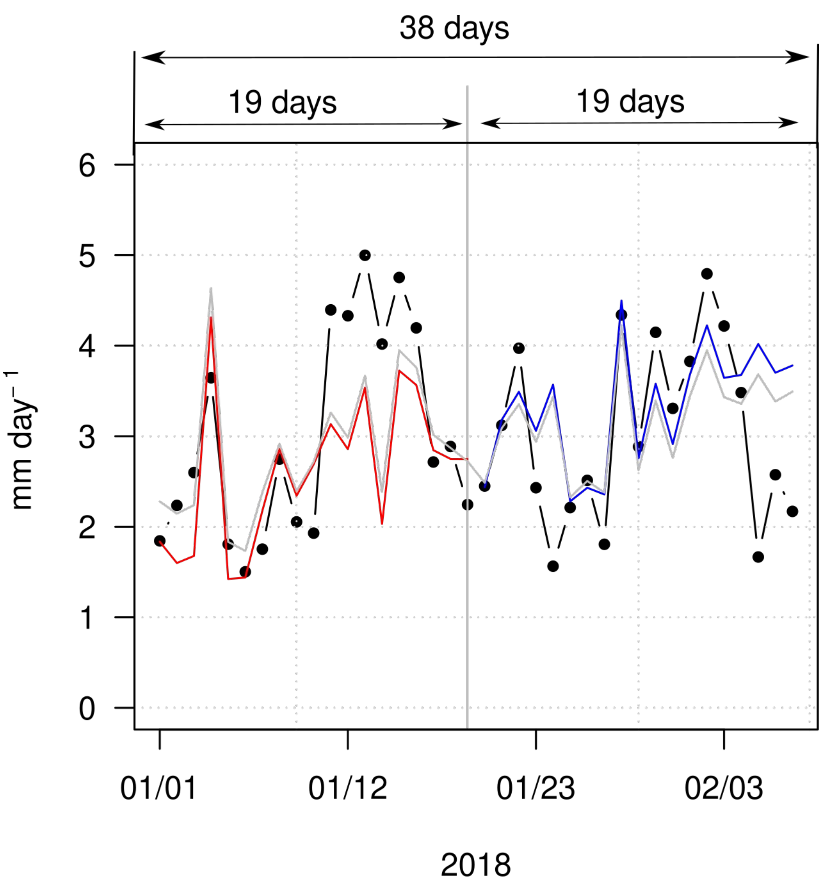


Figure 7. The daily series of the evaporation evaluated after applying the direct EC method (black) and applying the linear regression with the empirical coefficients estimated from data collected during various periods: 01.01.2018–07.02.2018 (grey), 01.01.2018–19.01.2018 (blue) and 20.01.2018–07.02.2018 (red).

Table 6 shows the estimates of the empirical coefficients in the linear relationship $a + b_1 w_2 + b_2 \left(e_s - e_2\right)$, which were calculated by applying three different data subsets (Fig. 7). The parameter b_1 is very similar, being estimated from three different subsets. The estimates of two parameters (a and b_2) are also similar for subsets 1 and 2. The estimates of the parameters varied substantially between subset 3 and the other two subsets. The value of the Pearson correlation coefficient is highest for subset 2, when the value of the residual standard error is minimal.

Table 6. Estimates of the efficiency indexes (R^2, R) and empirical coefficients (a, b_1, b_2) in the linear regression model to evaluate the daily series of evaporation based on the observations at the Maitri site.

Subset of observations	*a*	b_1	b_2	R^2	*R*	*RSE*	*RMSE*	*N*
Subset 1: 38 days	–0.37	0.40	0.88	0.40	0.37	0.84	–	35
Subset 2: 19 days	**–0.46**	**0.45**	**0.86**	**0.56**	**0.50**	**0.82**	**0.87**	**16**
Subset 3: 19 days	–1.20	0.44	1.21	0.28	0.18	0.89	0.91	16

Notation: *RSE* or a residual standard error is the average variation of points around the fitted regression line (the lower the RSE, the better the model); *RMSE* or a root square standard error is estimated as follows $\sqrt{\sum_{1}^{n}(E_{EC}-E_{mod})^2/n}$; *N* is the degree of freedom calculated as the length of the subset minus the number of empirical coefficients in the linear regression.

Furthermore, the day-by-day series of the evaporation were estimated with the empirical coefficients evaluated for subset 2 (bolded values in Table 6) for the whole of the field experiment. The sum of evaporation over the 38-day period is 120 mm, and it is over 5 % larger than the sum estimated after the direct EC method. The daily evaporation varies from 1.7 to 5.1 mm day^{-1}, with the average taking 3.2 mm day^{-1} and the standard deviation 0.8 mm day$^{-1.}$ This is only a bit larger than for the EC method.

4.3 Impact of katabatic winds on evaporation

The study region is dominated by winds from the southeasterly sector (Fig. 3 b). This corresponds to the katabatic winds, which the Coriolis force has turned left from the direct down-slope direction. We carried out further analyses on the wind conditions in the study region to better understand the impact of katabatic winds. We calculated the geostrophic wind fields for each day of the study period from the mean sea level pressure fields estimated from the ERA5 reanalysis. The results demonstrated that the geostrophic (synoptic) wind was mostly from the east, i.e., some 45 degrees right from the mean direction of the observed near-surface wind. This deviation angle may partly result from the Ekman turning in the atmospheric boundary layer that, over an ice sheet with a rather small aerodynamic roughness, may contribute some 20 degrees, and partly from the katabatic forcing. In any case, in most cases the observed near-surface winds resulted from the combined effects of synoptic and katabatic forcing, which supported each other. Hence, it is very difficult to robustly distinguish the impact of katabatic forcing on the near-surface winds over the lake.

However, the geostrophic wind direction was distinctly different, 240–350°, on the following days: 6, 8–10, 19 and 25–27 January. These days were related to transient cyclones centered northwest of the lake or to high-pressure centers northeast of the region under the study. The wind speed over the lake was strongly reduced (Table 7) during those days, because the katabatic and synoptic forcing factors opposed each other. The lake surface temperature was higher than usual, but the air temperature was lower. The latter is partly because, during events when the geostrophic and katabatic forcing factors support each other (sector 60–130°), the strong wind effectively mixes the atmospheric boundary layer. Vertical mixing results in higher near-surface air temperatures in stably stratified conditions that prevail over the ice sheet (Vihma et al., 2011). Also, the adiabatic warming during the downslope flow is a major factor contributing to higher air temperatures (Xu et al., 2021). The impact of adiabatic warming is also seen as lower relative humidity in cases when the geostrophic wind is from the sector 60–130°. Related to the compensating effects of air temperature and relative humidity, the specific humidity was not sensitive to the geostrophic wind direction. The effect of the wind speed dominated the effect of the lake surface temperature (which controls e_s in Eq. (3)), and evaporation was strongly reduced when the geostrophic wind was from the sector 60–130° (Table 7).

Table 7. The mean values of the evaporation (E_{EC}), the wind speed (w_2), air specific humidity (Q_2), and lake surface temperature (w_t) and air temperature (t_2) calculated over the days when the geostrophic wind direction was 60–130° and when it was 240–350°.

Geostrophic wind dir.	Evaporation (mm day^{-1})	w_2 (m s^{-1})	Q_2 (g kg^{-1})	w_t (°C)	t_2 (°C)
60–130°	3.1	6.9	2.0	3.6	–0.2
240–350°	1.3	2.3	2.0	4.8	–2.8

The katabatic wind was a quasi-persistent feature during the study period, and the major changes in the evaporation were driven by changes in the synoptic scale wind direction, which affected the local wind speed.

5 Discussion

The estimations of the lake volume of the glacial lakes and the time scale of their water exchange are sensitive to the uncertainties inherent in various methods applied to evaluate evaporation (Shevnina et al., 2021). Our study yielded estimates of the evaporation over glacial lakes in the summer after the direct EC method, and the results are based on the data collected during a field experiment lasting 38 days. These estimates of the evaporation were considered the most accurate (or reference) while estimating the uncertainties inherent in the indirect methods, including the bulk-aerodynamic method and three Dalton type empirical equations. The results after the bulk-aerodynamic method reached the best skill scores based on the efficiency indexes; however, it underestimated the daily evaporation by over 30 %. The efficiency of the selected Dalton type semi-empirical equations was low, and they underestimated the mean daily evaporation up to 72 %. We suggested ~~the~~ regional empirical relationship to simulate the evaporation from the observations at the nearest meteorological site and water temperatures measured in the lake. We suggested applying this regional empirical relationship in simulations of day-by-day series of evaporations over the ice-free surface of the lakes in Antarctica. We did not apply the energy balance method in this study, and we also plan to further use this method in estimations of the evaporation over the glacial lakes. It also allows evaluation of the uncertainties inherent in this method.

The evaporation over the lakes is practically measured at the monitoring sites with evaporation pans, which are not fully applicable in the polar regions. The EC method requires specific equipment not always possible to deploy and operate in the remote Antarctic continent. Hence, the evaporation (or sublimation) over the lakes is usually estimated only indirectly on the basis of the regular or campaign observations or numerical model experiments. Only a few studies exist of the evaporation over the lakes located in Antarctica. Borghini et al. (2013) propounded estimates of evaporation over a small endorheic lake located on the shore of the Wood Bay, Victoria Land, East Antarctica (70° S). This lake is of 0.8 m depth, and its surface has decreased more than twice from the late 1980s to the early 2000s (from 4.0×10^3 to 2.0×10^3 m^2). The lake is the landlocked type; therefore, the evaporation is an important outflow term of the lake's water budget. The authors use the semi-empirical equation given in Shuttleworth (1993) to calculate the evaporation from the ice-free water surface with data on the water temperature, air temperature, and wind speed collected during a few weeks in December 2006. The mean daily evaporation was estimated to be 4.7 ± 0.8 mm day^{-1}. These estimates resulted in the loss of the liquid water at 40 ± 5 % of the total volume of the lake during the observational period. The lake studied by Borghini et al. (2013) differed from Lake Zub/Priyadarshini, yet the daily evaporation rates are of the same order of magnitude, and one can even expect a much larger evaporation over the surface of the landlocked lakes than over the glacial lakes.

Shevnina and Kourzeneva (2017) used two indirect methods to evaluate the daily evaporation of two lakes located in the Larsemann Hills oasis, East Antarctica (69° S). Lake Progress and Lake Nella/Scandrett are of the glacial type; however, they are much deeper and larger in volume than Lake Zub/Priyadarshini, and over 30–70 % their catchments are covered by the glacier. The thermal regime of these glacial lakes is also different: Lake Nella/Scandrett and Lake Progress have partially lost their ice cover in austral summers when their surface water temperature is only 2–3 °C, which is lower than the water temperature over the surface of Lake Zub/Priyadarshini. The daily evaporation was estimated to be 1.8 mm day^{-1} and 1.4 mm day^{-1} on the basis of applying the energy budget method (Mironov et al., 2005) and the semi-empirical equation after applying Odrova (1979), respectively. It is concluded that the daily evaporation over the glacial lakes is underestimated by both indirect methods. Our results prove that the uncertainties of the semi-empirical equation after applying Odrova (1979) are the largest among other considered methods.

Faucher et al. (2019) evaluated the annual water budget for Lake Untersee, the Dronning Maud Land, East Antarctica (71° S). Lake Undersee, perennially frozen year round, is a glacial-type lake directly attached to the continental ice sheet. Lake Untersee is not a landlocked lake as mentioned in Faucher et al. (2019). The sublimation (evaporation) over the lake surface is estimated among other terms of its water budget. These estimations are based on two years of in-situ measurements using snow sticks. The authors estimated the water losses from the ice-covered surface of the lake due to sublimation from 400 to 750 mm $year^{-1}$. The daily evaporation from the lake surface is approximately 1.1–2.1 mm day^{-1}.

This study focuses on the evaporation over ~~the~~ glacial lake that is ice free for almost two summer months. The seasonal presence of the liquid water (i.e., in glacial lakes and iced "swamps") over the ice/snow-covered land surface affects the surface-atmosphere moisture exchange and surface radiative budget. A proper description of the land cover is a crucial element of numerical weather predictions (NWPs) and climate models, in which the overall characteristics of the land cover are represented by the surfaces covered by the ground, whether vegetation, urban infrastructure, water (including lakes), bare soil or other. Various parameterization schemes (models) are applied to describe the surface-atmosphere moisture exchange and surface radiative budget (Viterbo, 2002). Lakes have been recently included in the surface parameterization schemes of many NWPs (Salgado and Le Moinge, 2010; Dutra et. al., 2010; Balsamo et al., 2012) with known external parameters (location, mean depth) available from the Global Lake Database, GLDB (Kourzeneva, 2010; Kourzeneva et al., 2012). The information on only a few glacial lakes is included in the newest GLDBv3 version but not on any lakes found in Antarctica (Toptunova et al., 2019). Over 65 thousand glacial lakes were detected over the East Antarctic coast via satellite remote sensing in austral summer 2017, and most of them spread over the ice shelf and margins of the continental ice sheet (Stokes et al., 2019). For example, the total area of the glacial lakes in the vicinity of the Schirmacher oasis was over 72 km^2 in January 2017 (Fig. 8); the two largest glacial lakes ~~are~~ a similar size to the Schirmacher oasis itself. Such an amount of liquid water over the ice/snow-covered region may contribute to the additional source of the uncertainties inherent in the NWPs.

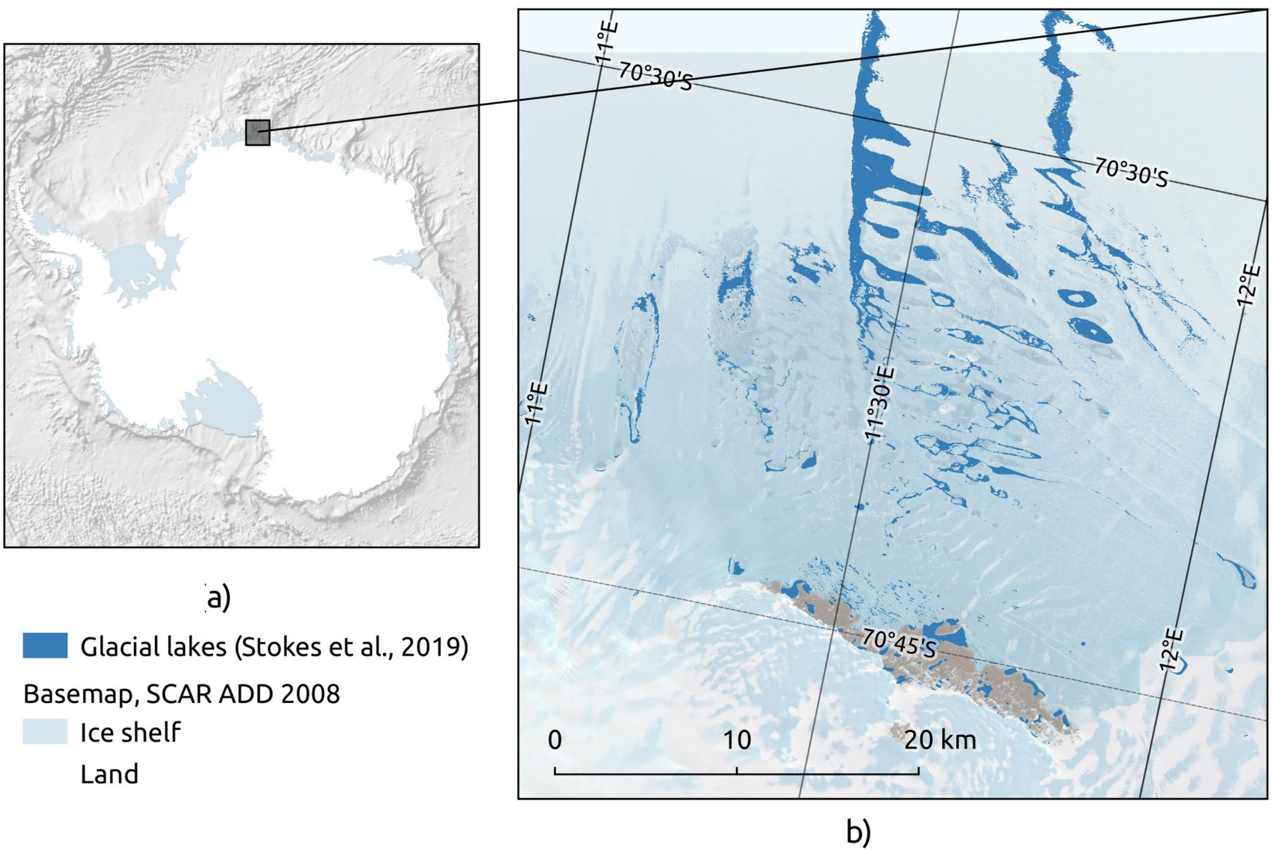


Figure 8. The glacial lakes over the surface of ice shelf in the vicinity of the Scirmacher oasis, East Antarctica.

The estimates of the evaporation are also available from atmospheric reanalyses that share the results of simulations performed by the NWPs. The most recent global atmospheric reanalysis is ERA5 of the European Centre for Medium-Range Weather Forecasts (Copernicus Climate Change Service, https://climate.copernicus.eu/, last access 09.07.2021; Hersbach et al., 2020). ERA5, as other reanalyses, does not assimilate any evaporation observations, but evaporation is based on 12 h accumulated NWP forecasts applying the bulk-aerodynamic method. The results naturally depend on the presentation of the Earth surface in ERA5, and in the Dronning Maud Land, the surface type is ice and snow with no lake. Therefore, the estimate of the evaporation does not include evaporation from liquid water surfaces. We also estimated the daily evaporation from the ERA5, and the results suggest that the evaporation during summer (DJF) 2017–2018 was 0.6 mm day^{-1}. It is only one-fifth of the evaporation estimated with the direct EC method.

Naakka et al. (2021) estimated evaporation over the Antarctic region from the ERA5 reanalysis for five domains, including the East Antarctic slope where the Schimacher oasis is located. The average daily evaporation in summer there is 0.3 mm day^{-1}, which is reasonable for the ice/snow-covered surface. The presence of the liquid water over the ice/snow-covered surface in the summertime changes the fraction of the lakes over the East Antarctic slope, and it is 6–8 % of the region in the vicinity of the Schimacher oasis (Fig. 8). The increasing numbers of the glacial lakes over the surface of the East Antarctic slope affects the surface-atmosphere moisture interactions, and it also changes the regional evaporation not accounted for by the numerical weather prediction systems and climate models. We assumed that the 0.3 mm of ERA5 is a fair value for the ice sheet in the East Antarctic slope and that 3 mm is a representative value for the glacial lakes. It may add up to 0.16–0.22 mm to the regional summertime evaporation over the margins of the East Antarctic slope. These numbers seem to be insignificant for the mass balance of the Antarctic ice sheet and shelf. However, we suggest~~ed~~ more comprehensive research to better understand the role of the glacial lakes on the surface-atmosphere moisture exchange and surface radiative budget of the ice cover in the polar regions.

6 Conclusions

This study ~~suggested~~ ~~the~~ estimates of summertime evaporation over an ice-free surface of the glacial lake by applying the direct eddy covariance (EC) method. The evaporation was also evaluated after the indirect methods, needing only a few hydrometeorological parameters monitored at selected sites (e.g., WMO stations) as input. Our study focused on the glacial Lake Zub/Priyadarshini located in the Schirmacher oasis, Dronning Maud Land, East Antarctica. The catchment of the lake includes less than 30 % of the area covered with the glacier and results in a specific thermal regime and water balance of the lake. We estimated the evaporation over the ice-free lake surface as 114 mm in the period from 1 January to 7 February 2018 after using the direct EC method. The daily evaporation was estimated to be 3.0 mm day^{-1} in January 2018. The largest changes in the daily evaporation were driven by the synoptic-scale atmospheric processes rather than by the local katabatic winds.

This study gave the estimations of the uncertainties inherent in the indirect methods applied to evaluate summertime evaporation over a lake surface. The bulk-aerodynamic method suggests the average daily evaporation to be 2.0 mm day^{-1}, which is over 32 % less than the result based on the EC method. The selected Dalton type semi-empirical equations underestimated the evaporation over the lake surface by over 40 – 72 %. We suggested applying ~~the~~ regional empirical relationship while estimating the summertime evaporation over the ice-free glacial lakes located in Antarctica. We also stress the need for accurate measurements of the surface water temperature in local lakes to support studies of the lake water budget and evaporation (sublimation).

The evaporation results were not sensitive to differences in the data collected at the meteorological site nearest to the lake and the site located on the lake shore. Hence, we suggest using the synoptic records at the meteorological site Maitri to evaluate the evaporation over the surface of Lake Zub/Priyadarshini. Field experiments are needed to make analogous comparisons of meteorological conditions between other glacial lakes and the permanent observation stations nearest to them. The water balance terms of the glacial lakes (including evaporation) are closely connected to their thermal regime, and coupled thermophysical and hydrological models are needed to predict the amount of water in these lakes. Our results also demonstrated the need to ~~present~~ glacial lakes in atmospheric reanalyses as well as numerical weather predictions (NWP) and climate models. Ignoring them in a lake-rich region, such as the Schirmacher oasis, results in a large underestimation of regional evaporation in summer.

Annex.

To evaluate the uncertainties of the EC method with the method of paired tower: the intercalibration experiment at Alqueva reservoir, Portugal.

The eddy covariance (EC) method has some errors and uncertainties associated with the nature of the measurement and the instrument system; therefore, the results must be treated with special attention. Nevertheless, the complexity of the method, namely the filters and corrections that this method requires (see Section 3.3), make it possible to reduce the errors and uncertainties. According to Aubinet et al. (2012), three methods quantify the total random uncertainty for the EC method: the paired tower, 24 h differencing, and the model residual. We apply the paired tower method in our study to evaluate the errors of the Irgason installed on the shore of Lake Zub/Priyadarsini. The intercalibration experiment lasted from 12 October to 25 October, 2018, and during this period two Irgason instruments were deployed on a floating platform in Alqueva artificial lake located southeast of Portugal.

The floating platform (38.2° N; 7.4° W) has been operating continuously since April 2017, and in this experiment, two eddy covariance stations (Irgason) were installed at a height of 2.0 m next to each other facing the same footprint (Fig. A1). In this experiment, we compare the measurements of the Irgason of the Finnish Meteorological Institute (FMI) to those collected by the Irgason of the Institute of Earth Sciences (ICT), University of Évora. Taking advantage of both instruments being identical, the settings were set exactly the same. The standard gas zero and span calibration was performed before the experiment. The raw measurements from both instruments were postprocessed applying the algorithm given in Potes et al. (2017). That allows precise estimates of random instrument uncertainty rather than total random uncertainty, which demands that both instruments are in the same area but with different footprints (Dragoni et al., 2006).

Figure A1: The instruments installed in Alqueva reservoir (Portugal) for the intercalibration. The instrument on the left belongs to Institute of Earth Sciences; the instrument on the right belongs to Finnish Meteorological Institute.

Figure A2 shows a scatter plot between a 30-minute evaporation evaluated after the measurements of two instruments during the intercomparison campaign that occurred in Alqueva reservoir. The correlation coefficient between the evaporation calculated after two Irgason is over 0.98, which suggests strong agreement between the measurements. Figure A3 presents the frequency distribution of the 30-minute evaporation random instrument uncertainty (ε_F) during the intercomparison campaign (see the Eq. 9 from Dragoni et al., 2007). The random instrument error in the 30-minute evaporation is estimated as the standard deviation of the evaporation random instrument uncertainty (ε_F), is 0.004324 mm. Thus, in relative terms, the intercomparison campaign allows us to obtain an estimate of the random instrument error of 7.0 %. This value is below other studies presented by several authors, namely, Eugster et al. (1997), whom used the same approach of the paired towers in

Alaskan tundra and obtained 9 % for latent heat flux; Finkelstein and Sims (2001), who presented a value between 14 and 35 % for latent heat flux in forest and agricultural sites; and Salesky et al. (2012), who found typical errors of 10 % for the heat flux.

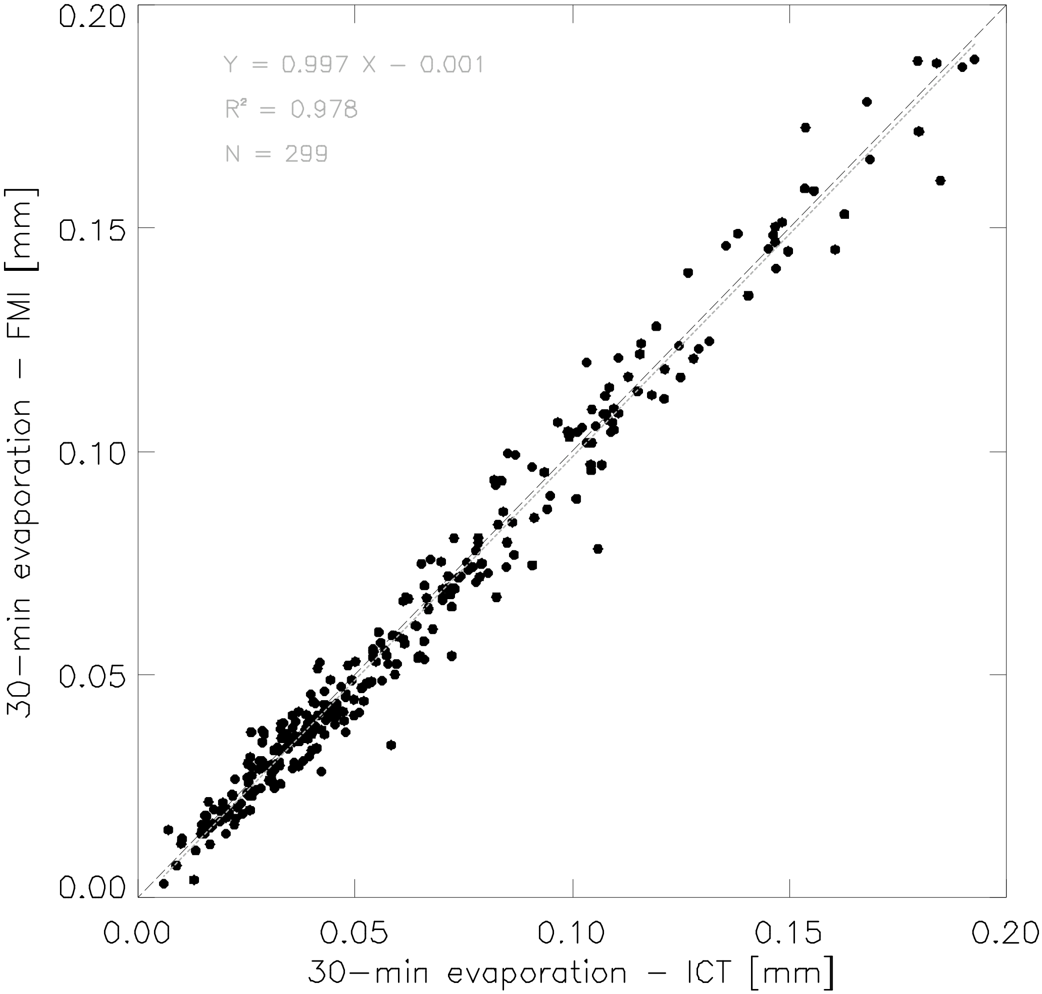


Figure A2: Scatter plot between 30-minute evaporation from both instruments: Y-axis is the values estimated after the measurements by the FMI Irgason, and X-axis is the values after the measurements of the ICT Irgason.

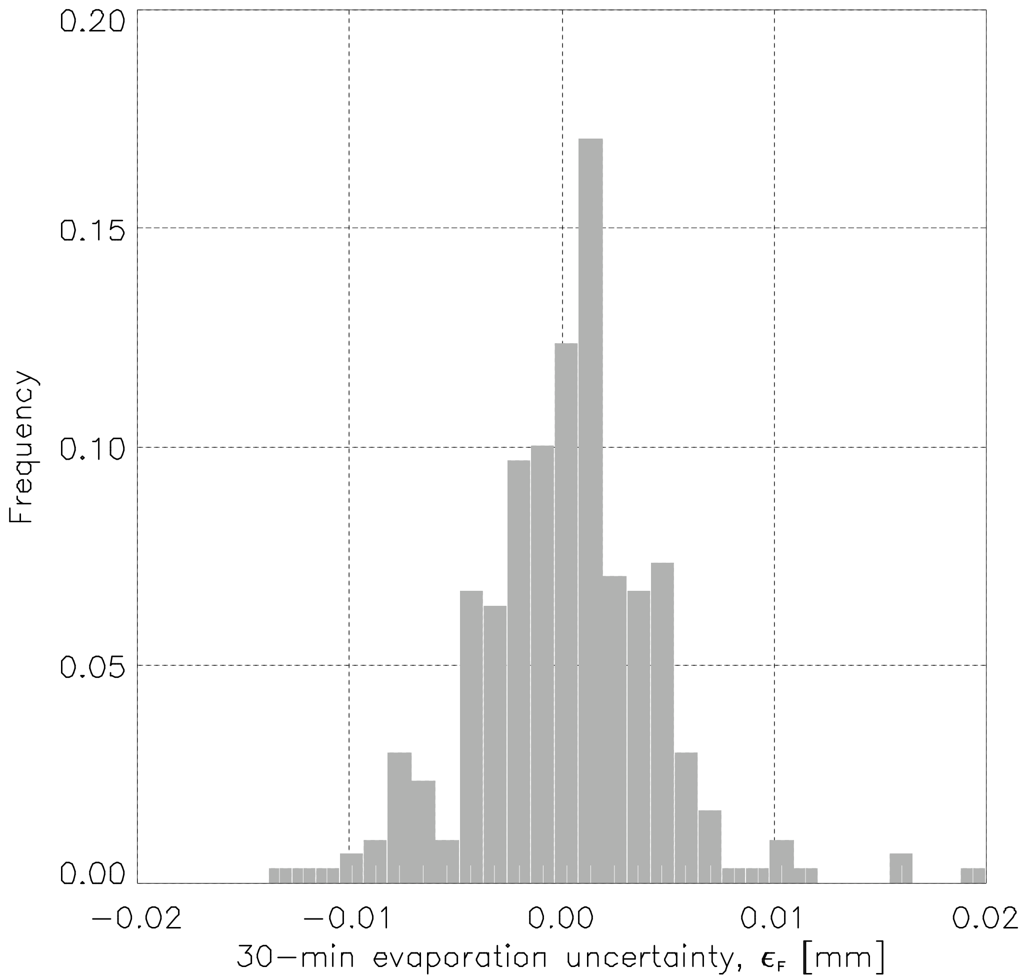


Figure A3: Frequency distribution of the 30-minute evaporation random instrument uncertainty (ε_F).

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Supplement. ES attached the calculation of the evaporation with the semi-empirical equations (Dalton_equations_results.csv) and code used to evaluate the estimates of the uncertainties inherent in various methods. MP has attached the post processed after the EC method (20180101_20180207_EC_FLUX.txt). TV attached the calculations after the bulk-aerodynamic method (Bulk_method_results_Irgason_input.txt and Bulk_method_results_Maitri_input.txt). PD have attached meteorological data measured at the Maitri site (Meteorological_Parameters_Summer_2017-18.xlsx) and the water surface temperature measured by Solinst instrument (Lake_Temperature_Solinst_Jan-Feb2018.xlsx). TN provides the series of the daily evaporation from ERA5 reanalysis at the grid note nearest to the Novo meteorological site (Evaporation_Schirmacher_Oasis_from_ERA5.csv). The supplement related to this article is available online at:

Data and code availability. The data and code used in this study are available in the Supplement. We also used two datasets stored at zenodo: http://doi.org/10.5281/zenodo.3469570 and http://doi.org/10.5281/zenodo.3467126.

Author's contribution. ES initiated the manuscript and collected the data in the field experiment 2017–2018. She also calculated the evaporation applying the semi-empirical equations. MP supervised the EC measurements in the field and carried out the calculations applying the EC method (including the intercalibration campaign). TV contributed with the estimations of evaporation applying the bulk aerodynamic method. TN contributed with analyses of evaporation based on ERA5. TV and TN performed the analysis of the impact of the katabatic winds. PD and PKT contributed with the analysis of the meteorological observations at Maitri site. All authors contributed to writing the manuscript.

Competing interests. The authors declare that they have no conflict of interest.

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