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Evaporation over glacial lakes in Antarctica

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Abstract. The water cycle in glacier hydrological networks is not well known in Antarctica. We present the first evaluations of evaporation over a glacial lake located in the Schirmacher oasis, Dronning Maud Land, East Antarctica. Lake Zub/Priyadarshini is a shallow lake of the epiglacial type, and it is ice free for almost two months in summer (December - February). We evaluated evaporation over the ice free surface of Lake Zub/Priyadarshini using various methods including the eddy covariance (EC) method, the bulk aerodynamic method, and Dalton type empirical equations. The evaporation was estimated on the basis of data collected during a field experiment in December–February, 2017–2018, and regular observations at the nearest meteorological site. The EC was considered as the most accurate method providing the reference estimates for the evaporation over the lake surface. The EC method suggests that the mean daily evaporation was 3.0 mm day^{-1} in January, 2018. The bulk-aerodynamic method, based on observations at the lake shore as an input, yielded a mean daily evaporation of 2.3 mm day^{-1} for January. One of the Dalton type equations was better in estimating the summer mean evaporation, but the bulk aerodynamic method was much better in producing the day-to-day variations in evaporation. The summer evaporation over the ice-free Lake Zub/Priyadarshini exceeded the summer precipitation by a factor of 10. Hence, evaporation is a major term of the water balance of glacial lakes. Evaluation of the evaporation products of ERA5 reanalysis clearly demonstrated the need to add glacial lakes in the surface scheme of ERA5. Presently the area-averaged evaporation of ERA5 is strongly underestimated in the lake-rich region studied here.

1 Introduction

With rising near-surface air temperatures and enhanced snow and ice melt, liquid water is increasingly more present over the margins of the Antarctic ice sheet. A large part of melt water accumulates in a population of glacial lakes (Golubev, 1976; Klokov, 1979; Hodgson, 2012). Recently, remote sensors and geophysical surveys have yielded evidence on a large number of glacial lakes both in Greenland and Antarctic ice sheets (Leeson et al., 2015; Arthur et al., 2020). These lakes appear over the surface of ice sheets (supraglacial type, e.g. Stokes et al. (2019) and Kingslake et al. (2017)), inside ice sheets (subglacial type) and alongside ice sheets (epiglacial/proglacial type) or ice shelves (epishelph type). The glacial lakes are connected by ephemeral streams into a hydrological network that may rapidly develop in the melting season (Lehnherr et al., 2018). After retreating of glaciers many epiglacial/proglacial lakes have become landlocked. The lakes of the landlocked type occupy local relief depressions over deglaciated areas also named as oases in Antarctica (Simonov, 1971; Hodgson, 2012).

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 of 1969-1978 (Klokov, 1979). Picard et al. (2007) evaluated the melting area over the continent on the basis of microwave remote sensing data during the austral summers 1979/80 to 2005/06. The authors concluded that over 25 % of the continent's surface melting has occurred at least five times during the last 27 years. Stokes et al. (2019) used remote sensing data to detect water bodies over the East Antarctic coast, and more than 65000 glacial (supraglacial type) lakes were found in the peak melting season 2017. The total area of these supraglacial lakes is over 1300 km^2, and most of them are located at low elevations.

The glacial lakes are a well known indicator for climate change (Verleyen et al., 2003; Williamson et al., 2009; Verleyen et al., 2012). During 2007–2016 mass loss from the Antarctic ice sheet tripled relative to 1997–2006 (Meredith et al., 2019), which may partly explain the recently observed increases in lake volume, depth and surface area for many epiglacial lakes located in the East Antarctic oases (Levy et al., 2018; Boronina et al., 2020). However, many landlocked lakes have decreased in their volume and surface area (Borghini et al., 2013; Shevnina and Kourzeneva, 2017). These changes in the physiographic parameters of glacial lakes (volume, surface area, depth) indicate effects of regional warming, and they also affect local biota and living forms (Castendyk et al., 2016). Possible effects of glacial lakes on the global sea level rise are not clear 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).

Among others, modelling approaches have been applied to understand local effects of climate warming to lake physiographic parameters. The water balance equation of a lake allows estimations of changes in the lake volume due to inflow and outflow terms (precipitation, evaporation, surface/subsurface inflow/outflow runoff, water withdrawal) measured or modelled. The water balance in Antarctic lakes is specific for each lake type, and different processes 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 both glacial and landlocked types of lakes are sensitive to uncertainties inherent to the methods applied to evaluate evaporation (Shevnina et al., 2021).

The evaporation is estimated only indirectly (Guide, 2008) from different techniques. At monitoring sites it is usually evaluated by applying evaporation pans or semi-empirical methods to estimate evaporation from meteorological observations (Braslavskiy, 1966; Keijman, 1974; Sene et al., 1991; Shuttleworth, 1993; Majidi et al., 2015). These methods include the bulk aerodynamic method, the energy balance method, the Dalton type semi-empirical equations and their combinations (Brutsaert, 1982; Finch and Hall, 2001). Among others, the eddy covariance (EC) method is recognized as most accurate in estimations of the evaporation. This method has been introduced for more than 30 years ago (Stannard and

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Rosenberry, 1991; Blanken et al., 2000; Erkkilä et al., 2018; Beyrich et al., 2006; Mammarella et al., 2010; Aubinet et al., 2012; Franz et al., 2018). The EC measurements of evaporation over the glacial lakes are rare.

Estimates on evaporation are also available from climate and numerical weather prediction (NWP) models and atmospheric reanalyses. 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). As other reanalyses, ERA5 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. Lakes have been recently included in the surface schemes of NWP models (Dutra et al., 2010; Mironov et al., 2010; Balsamo et. al., 2012) with lake parameters, such as location, mean depth and surface area, available from the Global Lake Database (Kourzeneva, 2010; Kourzeneva et al., 2012; Toptunova et al., 2019). However, the database does not include information on lakes located in polar areas including Antarctica. Hence, NWP models and reanalyses do not account for the glacial lakes seasonally formed over the margins of Greenland and Antarctic ice sheets, which results in errors in estimations of the atmosphere-surface exchange of water in two polar regions.

This study addresses summertime evaporation over the ice-free surface of a glacial lake evaluated by applying various methods namely the eddy covariance, the bulk-aerodynamic and Dalton type semi-empirical equations as well as ERA5 evaporation products. The EC measurements are used as a reference to evaluate the accuracy of the estimates with the bulk aerodynamic method, the semi-empirical equations and ERA5. This information is beneficial, as EC measurements over glacial lakes are rarely available, and other estimates have to be used. The EC measurements of evaporation were collected during a field experiment on the epiglacial Lake Zub/Priyadarshini located in the Schirmacher oasis, East Antarctica.

2 The study area, climate 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 (Fig. 1). 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. The total rocky area covers 21 km^2 (Konovalov, 1962). The relief is hillocks with absolute heights up to 228 m above sea level (asl). 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 (Simonov, 1971; Klokov, 1979; Srivastava et al., 2012).

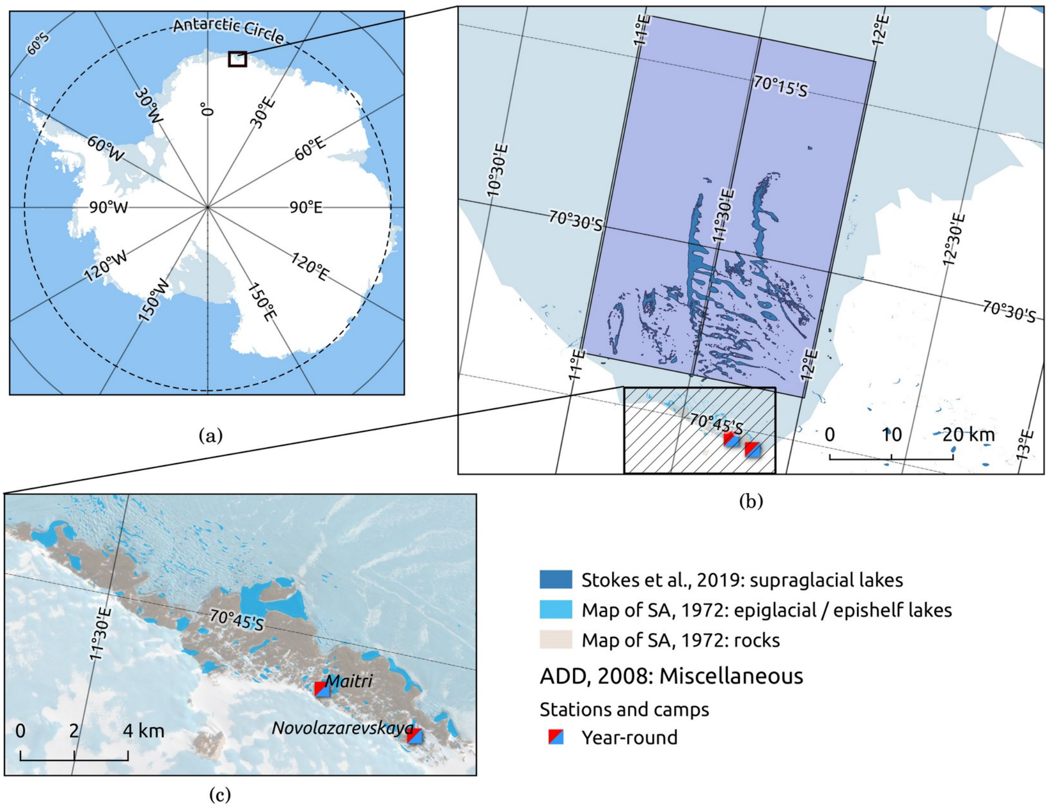

Figure 1: The study region: (a) Location of the Schirmacher oasis (SA); (b) the glacial lakes in the coast of the Dronning Maud Land; (c) the lakes in SA (after Map of SA, 1972) with Landsat Image Mosaic of Antarctica, LIMA given as the background.

The climate of the Schirmacher oasis is characterized by low air humidity and temperature, and 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). There are two meteorological observation sites operating in the Schirmacher oasis (Fig. 1 c). The meteorological observations were started in 1961 at Novolazarevskaya (Novo) site (70°46′36″S, 11°49′21″ E, 119 m elevation, Word Meteorological Organization (WMO) number 89512), and these observations are representative for the uphills of the oasis (Report of 31 SAE, 1986). Maitri meteorological site (70°46′00″S, 11°43′53″ E, 130 m elevation, WMO number 89514) opened in 1989, and is located over 5.5 km from Novo site. Both meteorological sites are included in a long-term monitoring network, and their measurements are done according to standards by WMO (Turner and Pendlebury 2004). Table 1 shows weather conditions during the austral summer 2017–2018 and climatology (1961–2020) of the Schimacher oasis according to the observations at Novo site (the data given by the Arctic and Antarctic Research Institute at http://www.aari.aq/default_ru.html, last access 03.06.2021).

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Table 1. Climate (1961-2020) and weather conditions during the summer 2017–2018 at the Novo station.

Parameter	Period	December	January	February
Air temperature, °C	climatology	-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,%	climatology	47 / 56 / 69	49 / 56 /66	41 / 49 / 59
	2017	50	–	–
	2018	–	57	49
Atmospheric pressure, Pa	climatology	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}	climatology	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, °C	climatology	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	climatology	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
Incoming solar radiation, W m^{-2}	climatology	865 / 975 / 1047	812 / 845 / 894	402 / 456 / 506
	2017	918	–	–
	2018	–	782	468

*Min / Mean / Max

January, 2018 was generally colder, less windy and less sunny than the climatology based on observations at Novo (Table 1). The precipitation and relative humidity were close to the climatology. The daily air temperatures ranged from –8.3 to 2.8 ºC, the wind speed from 1.5 to 14.3 ms^{-1}, with an average of 6.2 ms^{-1}. For the EC measurements, the wind direction is important to define a proper location to install the flux tower. We therefore calculated the wind direction from 6 hour synoptic observations at the Novo site with the data available from the British Antarctic Survey Dataset (https://www.bas.ac.uk, last access 14.12.2018) covering the period 1998–2016. Fig. 2 shows the wind direction and frequency of wind speed anomalies for the multi-year means for eight ranges, which were calculated for December and January. The prevailing wind direction ranged from 120 to 140º, and this circumstance was accounted for when deploying the measuring systems in the field experiment on the coast of Lake Zub/Priyadarshini.

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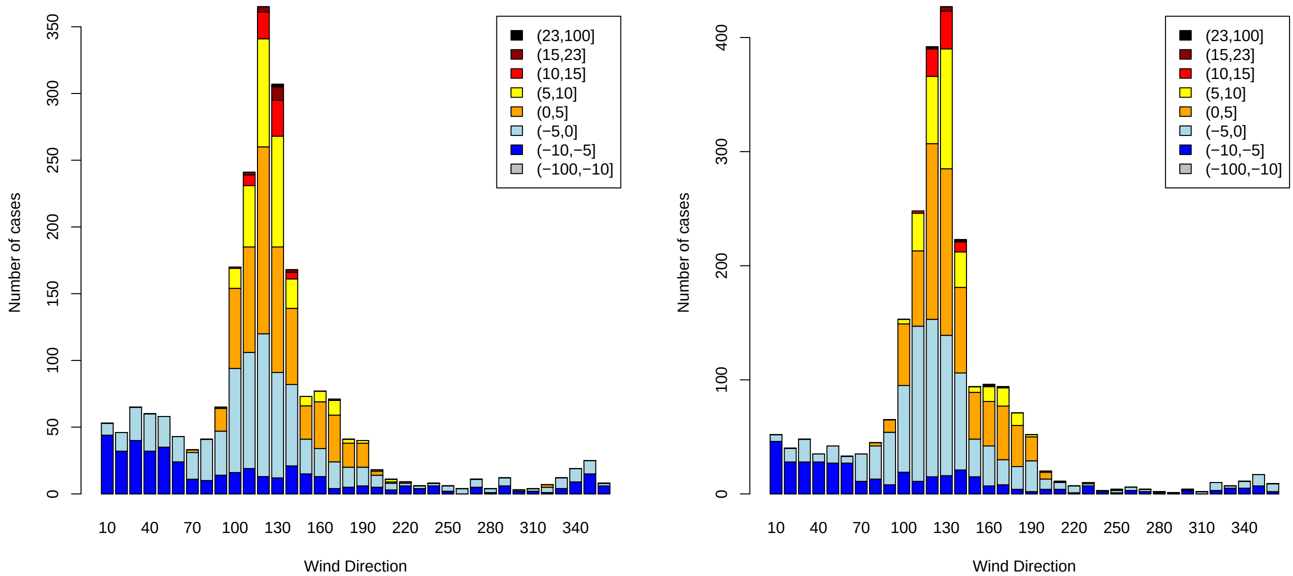

(a) (b)

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

For the summer season 2017–2018, the observations at Maitri site were very similar to those at Novo site (Fig. 3). The correlation coefficient between the daily series of the air temperature, relative humidity and wind speed vary from 0.95 to 0.98. According to the Maitri meteo 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 %. Sect. 4.1 further addresses the differences in temperature, humidity and wind measured at the experimental site located on the lake shore and at Maitri site.

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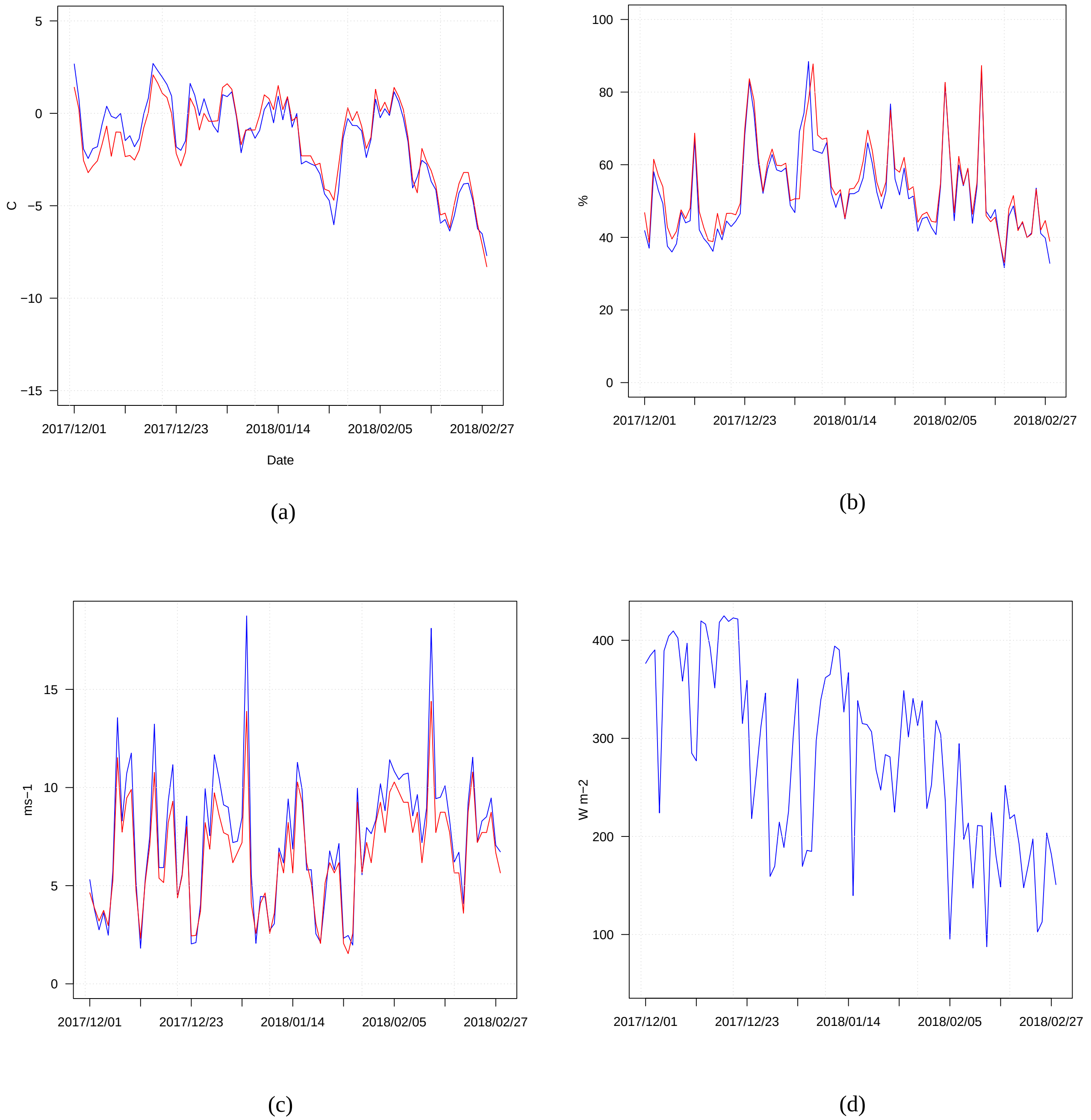

Figure 3: The meteorological conditions during the summer 2017–2018 according to the observations at Novo (blue line) and Maitri site (red line): (a) air temperature; (b) relative humidity; (c) wind speed; (d) incoming solar radiation.

More than 300 lakes are mapped in the oasis (Fig. 1 c), and many of the epiglacial lakes are ice free in summertime for almost two months (Map of SA, 1972; Kaup et al., 1988; Richter and Borman, 1995; Kaup et al., 1995; Kaup, 2005; Khare et al., 2008; Phartiyal et al., 2011). The lake physiography is available from bathymetric surveys for only the largest lakes (Simonov and Fedotov, 1964; Loopman et al., 1988; Sokratova, 2011; Asthana et al., 2019). The catchments of the epiglacial lakes include different portions of the glaciated area, and it affects their thermal regime and water balance (Simonov, 1971; Krass, 1986; Shevnina et al., 2021). The lakes with a high portion of the glaciated area in their catchments can be fully ice covered during the summer seasons while the lakes with low portions of the glaciated area are usually free of ice in January–February. Via satellite remote sensing over 3000 supraglacial type lakes have been detected in the vicinity of the Schirmacher oasis, and most of them have spread over the ice shelf (Stokes et al., 2019). In January 2017, the total area of these lakes is over 72 km^2 in the region covering over two grid cells in the ERA5 (the shadowed box in Fig. 1 b).

This study focuses on the estimation of evaporation on the surface of the epiglacial Lake Zub/Priyadarshini. The lake is among the largest and warmest water bodies of the Schirmacher oasis. The lake catchment includes a low portion of glaciated area, and results in a specific thermal regime and water balance of the lake. The lake stays free of ice for almost two summer months from mid-December to mid-February. The water temperature in the lake rises up to 8–10 ºC in January, which is typical for the landlocked type lakes (Simonov, 1971; Borghini et al., 2013; Shevnina and Kourzeneva, 2017). Lake Zub/Priyadarshini occupes a local depression, and is fed by two inflow streams present in warm seasons. The outflow from the lake occurs via a single stream. The surface area of the lake is 33.9 $x10^3$ m^2, and its volume is over 10.0 $x10^3$ m^3 (Khare et al., 2008).

3 Field experiment, data and methods

3.1 Field experiment

During the field experiment in January–February, 2018, we collected the measurements needed for evaluation of the water balance terms of the lake including the evaporation over the lake surface during the ice free period. The observational network included water level/temperature gauges, water discharge/level gauges and an evaporation gauge (Fig. 4 a). The evaporation gauge was a flux tower equipped with an Irgason EC measurement device by Campbell Scientific (Instruction manual available at https://s.campbellsci.com/documents/ca/manuals/irgason_man.pdf, last access 09.07.2021). The Irgason consists of a 3D sonic anemometer and two gas analysers measuring CO2/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 to the shoreline of Lake Zub/Priyadarshini for the period of 1 January to 7 February, 2018 (Shevnina, 2019). The 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. 4 a). The Irgason was deployed on the boom at the height of 2 m, and it was fixed with 6 metal guidelines angled 120° to each other (Fig. 4 b).

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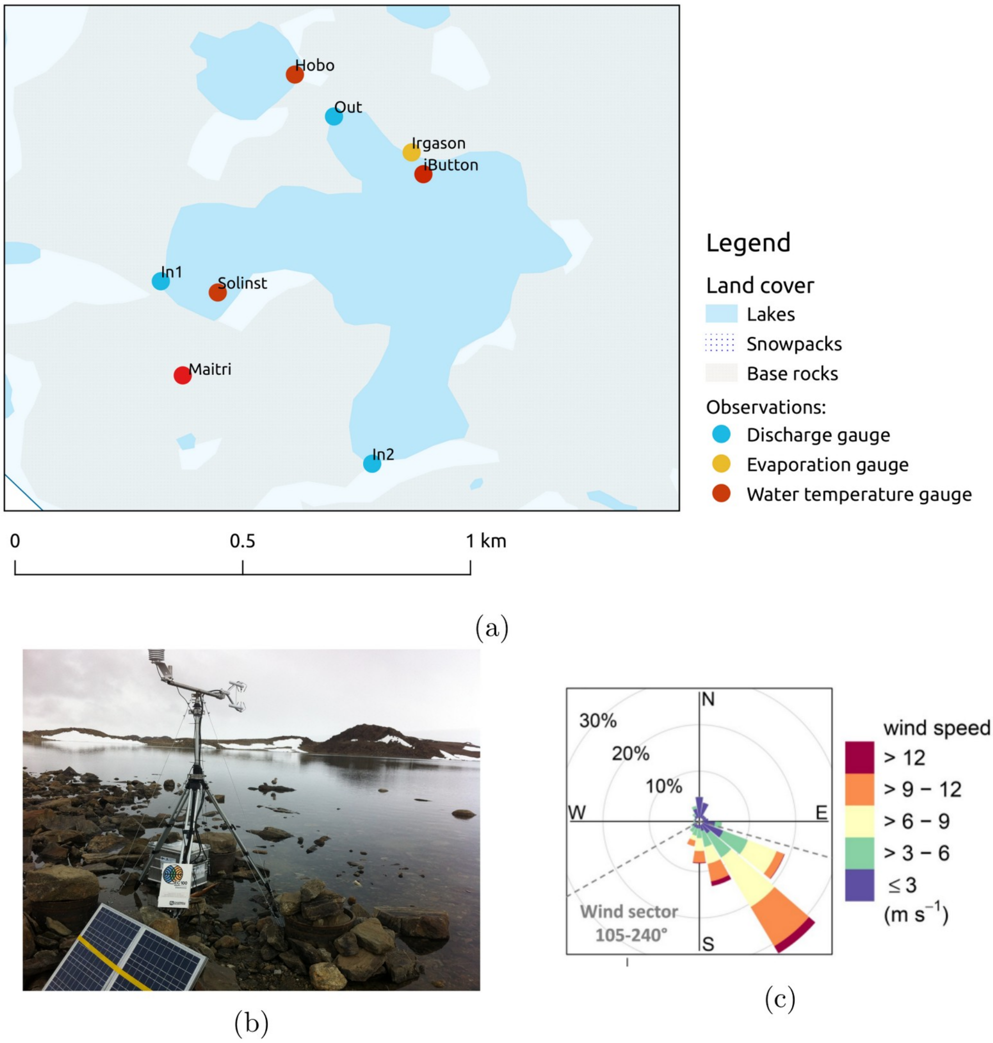

Figure 4: The experiment on the coast of Lake Zub/Priyadarshini: January-February, 2018: (a) meteorological and hydrological observational network; (b) Irgason deployed on the lake shore (06.01.2018); (c) wind speed and direction measured at Irason site, dashed line indicates the footprint wind sector.

For the EC method, the footprint is an important concept to evaluate the fluxes correctly (Burba et al., 2016). The footprint is defined by a sector of wind direction covering the source area, and depends on the height of the sensors (Kljun et al., 2004; Burba, 2013). We selected the Igrason deployment site on the basis of the prevailing wind directions (Fig. 2 b), so that for most of the time the wind is from the source area covered by the lake surface. We filtered out data outside the footprint (Fig. 4 c), and 2 m height of the Irason allows for a blind zone near the tower, therefore the stones on the lake shore do not affect the fluxes. The raw data by Irgason consisted of the values measured at a frequency of 10 Hz. We used these raw data to

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calculate a 30 minute series of the turbulent fluxes of momentum, sensible heat and latent heat, as well as air temperature, wind speed, and wind direction.

Applying many indirect methods, also lake water surface temperature data were needed, and temperature sensors were deployed in the lake (Hobo, Solinst and iButton in Fig. 4 a). These temperature sensors were installed at the depths of 0.2 m (Hobo and iButton) and 3.9 m (Solinst). The Solinst sensor was installed close to the pump station of Maitri, the Hobo in the neighbouring lake close to the inflow stream originating from Lake Zub/Priyadarshini, and the iButton 30–35 meter off the lake shore (Fig. 4 a). The data gathered by the sensors cover various observational periods lasting from 14 to 45 days (Table 2). Two temperature sensors 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.

Table 2. The hydrological and meteorological data collected during the field experiment in the summer 2017 – 2018.

Site / Sensor (Fig. 4 a)	Measured variables	Period
Irgason site	Air temperature, °C; H_2O concentration, g/m^3; 3D wind speed, ms^{-1}	01.01.2018 – 07.02.2018
Hobo	Water temperature, °C	30.12.2017 – 09.02.2018
Solinst	–	01.01.2018 – 15.12.2018
iButton	–	27.01.2018 – 09.02.2018
Maitri site	Air temperature, °C; wind speed, ms^{-1}	01.12.2017 – 28.02.2018

3.2 Data

The evaporation over the surface of the epiglacial Lake Zub/Priyadarshini was estimated on the basis of the data collected during the field experiment at a measuring site located on the lake shore (Irgason site). In addition, the air temperature and wind speed measured at the Maitri site and the lake shore were applied to evaluate the daily evaporation. The daily mean values of the air temperature and wind speed at the lake shore and Maitri were close to each other (Fig. 5 a and 5 c). However, the relative humidity measured at the Maitri site differed from those estimated from the concentration of water vapor and air temperature measured at Irgason site (Fig. 5 b). The difference between the relative humidity measured at Irgason site and Maitri site is 4.5 % on average. Such a difference in the relative humidity measured at these two sites may be due to the difference in the height of the sensors. At the Maitri site, the relative humidity sensor is installed at the height 6 meter above ground surface, while Irgason is installed at the height of 2 m on the lake shore. Therefore, the sensor at Maitri station is over 10–12 m higher than the sensor of Irgason. Also, the Irgason is located at the lake shore where air comes across the lake, and it may increase humidity at the Irgason site. The relative humidity measured at Maitri site is in agreement with the observations of Novo site for almost the whole summer period of 2017–2018 (Fig. 3 b).

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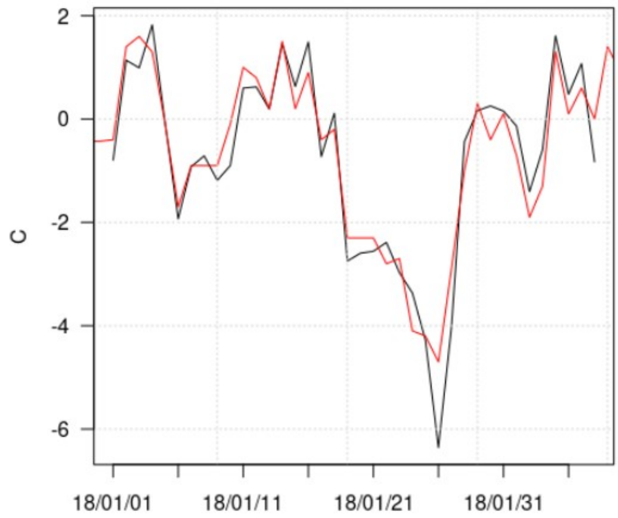
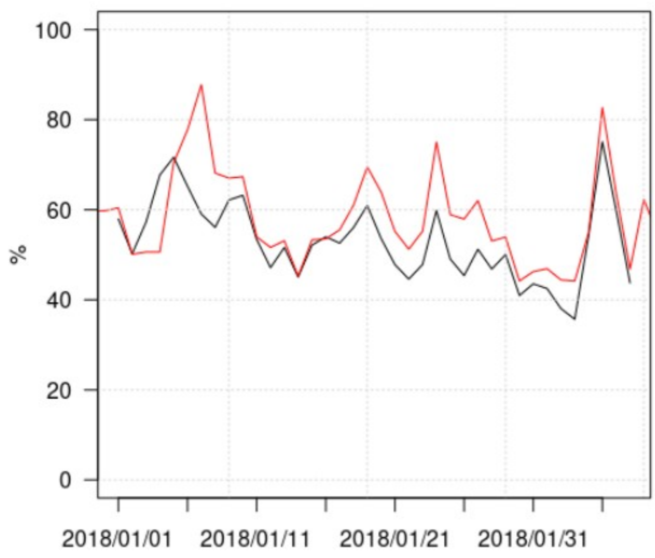


(a)



(b)

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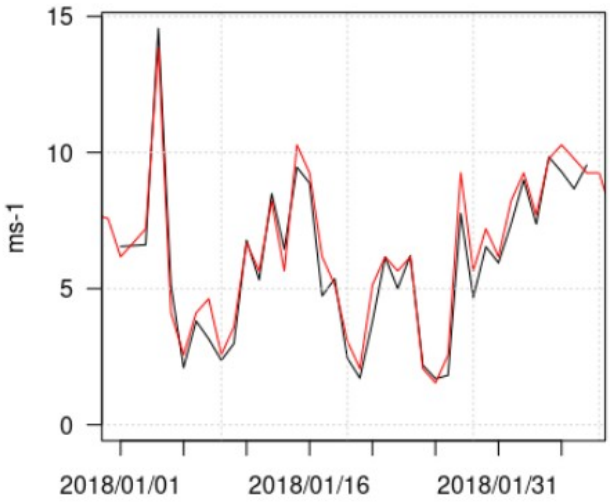

(c)

Figure 5: Daily time series of the meteorological parameters according to measurements at Irgason (black) and Maitri site (red): air temperature (a), relative humidity (b), and wind speed (c).

Figure 6 shows the daily time series of the water surface temperature measured by three sensors during the period of the experiment. The best agreement was found for the water temperature sensors Hobo and iButton (Fig. 6 a) with the correlation coefficient equaling 0.89. However, the period with simultaneous observations for Hobo and iButton is relatively short (14 days). The water temperature measured by Solinst sensor is systematically lower than those measured by Hobo and iButtons (Fig. 6 b). This circumstance is likely connected to the effect of the cold water incoming with the inflow stream, which is incoming close to the deploying place of this temperature sensor. This inflow stream results from the small epiglacial lake located upstream of Lake Zub/Priyadarshini. The inflow stream is fed by melting of seasonal snow and lake ice, and therefore its water is colder than in Lake Zub/Priyadarshini itself. Therefore, we further used the water temperature from the measurements collected by Hobo and iButton in calculating the evaporation applying the indirect methods. Hobo sensor allows measuring temperature with the accuracy 0.1 °C, and iButton sensor measures with the accuracy of 0.5 °C. During the period of 14 days with the simultaneous observations, the difference in the measurements gathered by Hobo and iButton sensors is 0.4°C on average, therefore we further used the longest series of the water temperature to estimate the evaporation.

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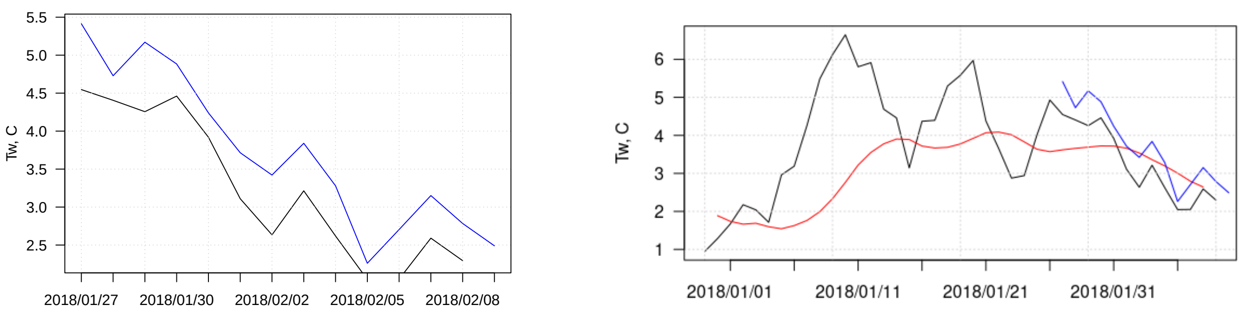

(a) (b)

Figure 6: Lake water surface temperature measured by three sensors: Hobo (black), iButton (blue) and Solinst (red) for the period of 14 days (a) and 38 days (b).

3.3 Methods

To evaluate the daily evaporation with the EC method, we used the data collected by the Irgason instrument installed on the shore of Lake Zub/Priyadarshini. The Irgason raw data were measured with a frequency of 10 Hz, and they required post processing. We followed Potes et al. (2017) in the post processing procedure of the raw data, which were further filtered in three steps: in the first step, the bad data with less than 50 % of total 10 Hz measurements were excluded; on the second step, we excluded all data automatically flagged for low quality, and the data with the gas signal strength 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 rarely observed in Antarctica. On the third step, the raw data were processed to remove spikes after the method by Vickers and Mahrt (1997). This procedure was repeated up to 20 times, or until no more spikes were found. Finally, the 30-minute values 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 were obtained (see the Supplement). To account for only those values collected within the lake surface area, we also filtered the data outside the footprint, which covered the winds with the direction ranging from 105 to 240º (Fig. 4 c). Only 18 % of the total measurements were excluded from further consideration after three steps filtering, and we replaced these values with the median. Finally, the daily evaporation over the lake surface was estimated as the sum of 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.

In the bulk aerodynamic method, the evaporation (kg m^{-2} s^{-1}) is defined 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 (ie. 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 after the bulk-aerodynamic method was calculated as follows :

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

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 m). For the turbulent transfer coefficient for moisture under neutral stratification (C_{EzN}), and we applied the value of 0.00107 based on measurements over a boreal lake (Heikinheimo et al., 1999; Venäläinen et al., 1998). It 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 value of C_{Ez}, taking into account the effects of thermal stratification, was calculated from the neutral value as follows:

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

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_q) 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 m, and converted to our observation height of 2 m 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 the height of 2 m:

$$E = C(e_s - e_{200}) \quad (3)$$

where, E is daily evaporation, mm day^{-1}; e_s is the water vapor saturation pressure; e_{200} is the water vapor pressure at 2 m height; C is a coefficient depend on meteorological conditions (often only the wind speed), and it is evaluated from observations with empirical approximations (Finch and Hall, 2001; Guidelines, 1969). We applied three semi-empirical equations to calculate the daily evaporation rate suggested by Penman (1948), by Doorenbos and Pruitt (1975) and by Odrova (1979), the Eqs. 4 – 5 respectively:

$$E = 0.26(1 + 0.54w)(e_s - e_{200}) \quad (4)$$

$$E = 0.26(1 + 0.86w)(e_s - e_{200}) \quad (5)$$

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$$E = 0.14\left(1+0.72\,w\right)\left(e_s - e_{200}\right) \quad (6)$$

where w is the wind speed measured at the 2 m heigh, e is the water vapor saturation pressure, calculated according to the Tetens's formula (Stull, 2017), is given in millibars, and E is the evaporation expressed in mm day^{-1}.

In the case of both the bulk-aerodynamic method and the semi-empirical equations, we calculated the evaporation rate separately using the meteorological observations collected at the Maitri site and at the lake shore (Igrason site). We calculated the daily series of the evaporation from the 30-minute series of the meteorological data in the estimations of the efficiency of the bulk aerodynamic method and the semi-empirical equations. In this study, the estimates of evaporation applying these methods were compared to the reference (EC) method in order to find the method with the lowest uncertainty. We used the Pearson correlation coefficient, the Nash-Sutcliffe efficiency index (Nash and Sutcliffe, 1970), and the s-sigma criteria after Popov (1979) to estimate the efficiency of the bulk aerodynamic method and semi-empirical equations.

Errors of the estimation of the evaporation after any method consist of systematic and random uncertainties. The meteorological parameters measured at Irgason site were very similar to those measured at Maitri site, therefore not significant systematic errors in the evaporation values. To quantify the random uncertainty for the eddy covariance method, three methods are usually applied (Aubinet et al., 2012). In this study, we used the method of paired tower to evaluate the uncertainties of the EC method, and we estimated the relative errors to be over 7 % (see the Annex). Even the EC method itself has some errors and uncertainties but is the most versatile and accurate method to measure the evaporation. The large number of filters and corrections that we applied to the EC data allowed us to reduce the errors and uncertainties. Also, the uncertainties of the EC method account for the errors due to filtering the measurements to those covered by footprint area. If evaporation during those times when wind direction is not from the lake is notably smaller due to meteorological conditions (higher air specific humidity and/or weaker winds) and when evaporation during those times are replaced by median evaporation, it could cause small overestimation in mean evaporation.

In ERA5 each model grid cell has been divided into tiles regarding surface types (Viterbo, 2002). The surface types include several land cover types such as ice or snow, vegetation, lakes or coastal water, and the ocean. As the surface properties are different on each surface type, heat and moisture surface fluxes are modelled separately for each type i.e. each tile. However, in the Dronning Maud Land, the surface type is ice and snow with no lakes. Therefore the estimate of the evaporation does not include evaporation from liquid water surface. Hence, we expect that the evaporation with the data of the ERA5 differs from the estimates after the EC method, and this study will quantify these differences.

In addition to the lack of glacial lakes in ERA5, the meteorological values applied in the calculation of evaporation (applying the bulk aerodynamic method) may somewhat differ from those observed at Maitri or at the lake shore. The Maitri and Novo data are regularly assimilated in ERA5, but the reanalysis values represent a combination of the background field (based on a previous short-term forecast) and the data assimilated. Also, the ERA5 values represent a grid cell of approximately 30 x 30 km instead of a single point. Therefore, it is not possible to apply traditional efficiency indices when comparing the results of ERA with those based on the field experiment on a single lake.

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4 Results

4.1 Weather conditions

During the period of the experiment, the wind was mostly blowing from the South-East sector with a mean speed of 6.0 to 6.4 ms^{-1}, and a mean air temperature of –0.8 °C (Table 3). There were several wind storms lasting up to a couple of days on 2–3 of January, 2018, 3–4 February, 2018. During these storms, the measured wind gusts reached up to 30 m s^{-1}. During the period of the experiment, the air temperature ranged from 1.5 to 14.6 °C, and the wind speed varied from 1.5 to 14.6 m s^{-1}. The atmospheric conditions over the lake were characterized by unstable stratification, with the lake surface temperature typically exceeding the air temperature by 4–5 ºC.

Table 3. The meteorological and hydrological parameters measured at the water balance sites in Lake Zub/Priyadarshini and the Maitri site: the summary statistics for the daily series. ("–" indicate no measured)

Variable name	Site: Irgason	Site: Maitri	Site: Hobo	Site: iButton**	Site: Solinst
Wind speed, ms^{-1}	1.7 / 6.0 / 14.6*	1.5 / 6.4 / 13.9	–	–	–
Wind direction, °	/ 150 /	/ 151 /	–	–	–
Relative humidity, (%)	28 / 42 / 56	44 / 58 / 88	–	–	–
Air temperature, C	-6.4 / -0.8 / 1.8	-4.7 / -0.7 / 1.6	–	–	–
Water temperature, °C	-	-	0.9 / 3.7 / 6.6	2.3 / 3.7 / 5.4	1.5 / 3.1 / 4.1

*Minimum / Mean / Maximum; ** water temperature was measured within the period of 14 days in January, 2018.

The time series of the 2 m wind speed over the lake shore demonstrated combined effects of synoptic-scale variations and a diurnal cycle. The diurnal cycle of evaporation coincided with the cycle of the wind speed, with the maximum observed between 6:00–9:00 hour in the morning (Fig. 7). The wind in these hours is of katabatic origin. In the morning hours the air temperature is below zero, and the temperature difference between the lake surface and the ambient air reaches its maximum. In combination with high wind, this temperature contrast leads to intensive evaporation during the morning hours. We suppose that the wind is the main factor affecting variations in evaporation over the lake surface in summer.

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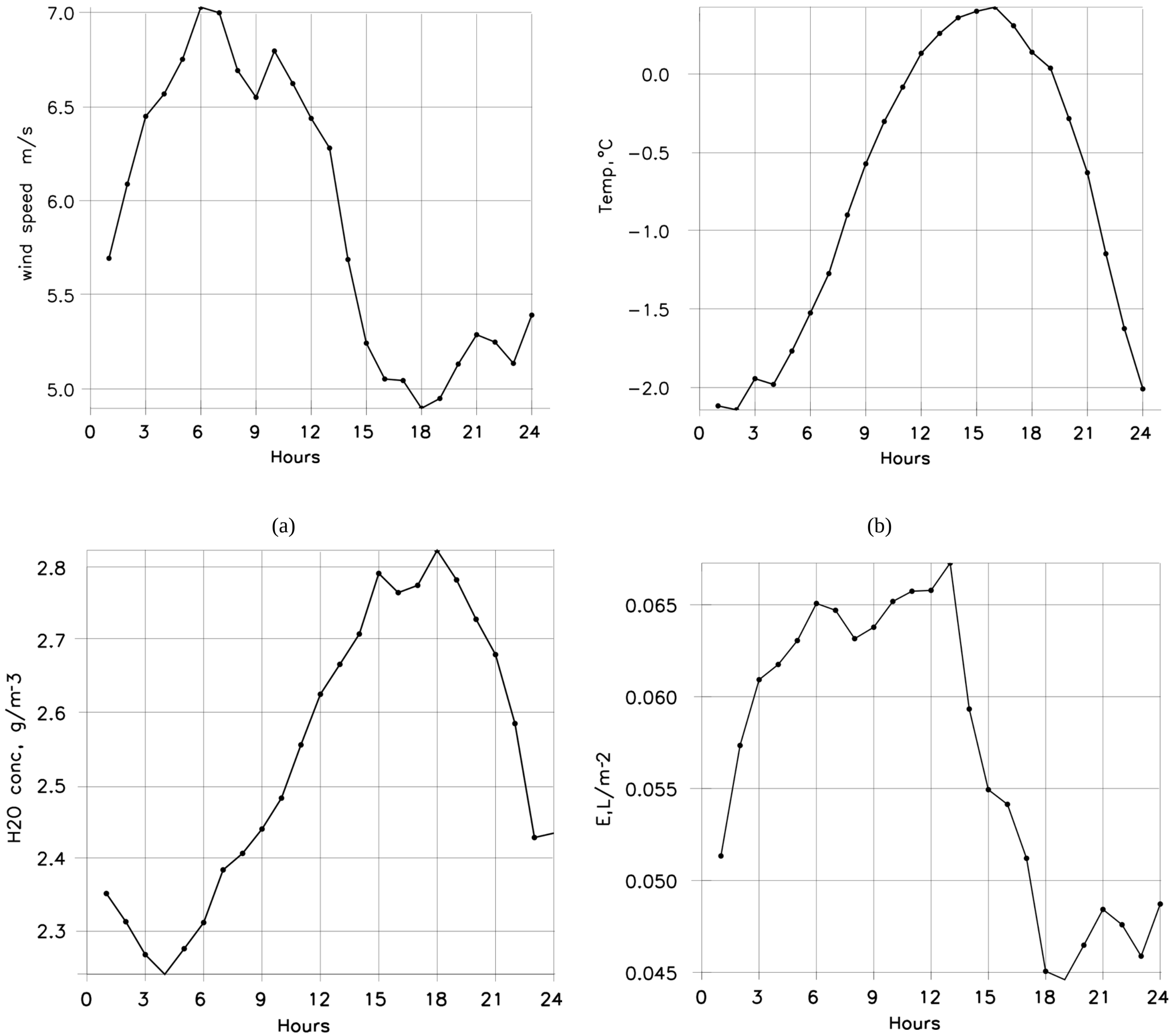

(a) (b)

(c) (d)

Figure 7: Diurnal cycles of the wind speed (a), the air temperature (b), the H2O concentration (c), and the evaporation (d).

4.2 Evaporation

We considered the eddy covariance method the most accurate, providing the reference estimates for the evaporation over the lake surface (Finch and Hall, 2005; Tanny et al., 2008; Rodrigues et al., 2020). Hence, we estimated the accuracy of the indirect methods by comparing their results with those based on the EC method. According to the EC method, the daily evaporation rate varied from 0.05 to 5.0 mm day^{-1} with the mean value equal to 3.0 ± 1.1 mm day^{-1}. Over the period of 38 days, it results in 114 mm of water evaporating over the lake surface.

The bulk aerodynamic method suggests the mean daily evaporation to be 1.9–2.1 mm day^{-1}, which is 37 % less than the result based on the EC method. Among the Dalton type semi-empirical equations, only the method by Doorenbos and Pruitt (1975) yielded good estimates for the daily evaporation over the lake surface. In case of using the meteorological observations at Irgason site, the average daily evaporation was 3.0 mm day^{-1}, and the evaporation sum over the period of the experiment is almost equal to those for the evaporation sum estimated applying the EC method. This method also suggests 10 % overestimation of the average daily evaporation in case of the meteorological input parameters from the Maitri site. The semi-empirical equations by Odrova (1979) and Penman (1948) underestimated evaporation both in the case of meteorological parameters measured at Maitri and at the Irgason site (Table 4) for 24–48 %. Odrova (1979) yielded the maximal (over 50 %) underestimation. The ERA5 data suggest that the evaporation during summer (DJF) 2017–2018 was 0.6 mm day^{-1}, which is only one fifth of the evaporation estimated with the direct method. The ERA5 evaporation rate was below 1.5 mm day^{-1} almost every day during summer 2017–2018.

Table 4. The daily evaporation (mm day^{-1}) calculated after 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).

	Input data: Irgason site			Input data: Maitri site		
Methods	Min/Max	Mean ± *SD*	Sum	Min/Max	Mean ± *SD*	Sum
Bulk-aerodynamic method	0.6 / 3.5	2.1 ± 0.8	78	0.7 / 4.0	1.9 ± 0.7	72
Penman, 1948	0 / 3.5	2.1 ± 0.8	81	0.3 / 4.2	2.3 ± 0.9	87
Doorenbos and Pruitt, 1975	0 / 5.1	3.0 ± 1.2	115	0.4 / 6.3	3.3 ± 1.4	126
Odrova 1979	0 / 2.3	1.4 ± 0.6	54	0.1 / 2.9	1.5 ± 0.6	59

SD is the standard deviation.

Since the ERA5 has a horizontal resolution of approximately 30 x 30 km, it cannot accurately resolve evaporation over a complex surface. The surface area of the epiglacial and ephishelf lakes in the Schirmacher Oasis is approximately a couple of tens square kilometres, which is small compared with the grid cell area of ERA5, approximately 900 km^2. However, considering the surface area of the supraglacial lakes formed during warm seasons, which total area in vicinity of the Schrmacher oasis is over 80 km^2 (the shadowed box in Fig. 1 b), the glacial lakes contribute approximately 4–5 % to the total area of the grid cell in the ERA5. The surface on the Schirmacher oasis during summertime is mostly snow free and thus has a low albedo, which results in a large gain of energy due to absorbed solar radiation. Instead, the closest grid cell in ERA5 has a large surface albedo, and consequently less than 17 % of the daily incoming solar radiation is absorbed to the surface, which may be representative for surrounding ice and snow covered areas but not for the glacial lakes located in the Schirmacher oasis area and its surrounding.

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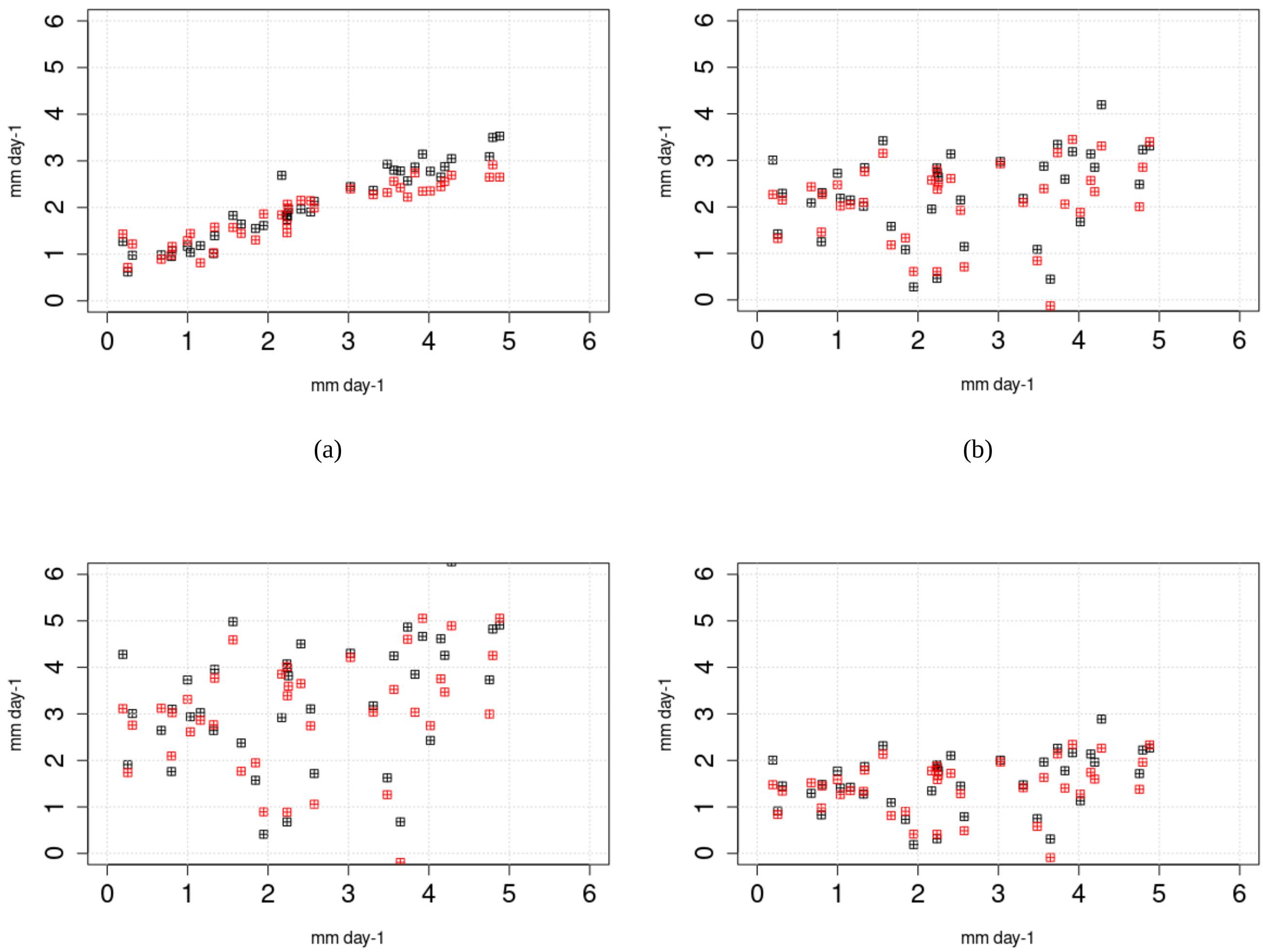

Figure 8: Scatter plots of the daily evaporation estimated with the indirect methods (Y-axis) against the EC method (X-axis): (a) the bulk aerodynamic; (b) Penman; (c) Doorenbos and Pruitt; (c) Odrova. The red dots indicate the estimates of the evaporation with the meteorological parameters measured at WMO synoptic site Maitri, which is the nearest to Lake Zub/Priyadarshini. The black dots indicated those estimates of the evaporation done with the meteorological parameters measured at Irgason site.

Figure 8 shows the relationship between the time series of daily evaporation estimated with different methods. The uncertainties in the estimates of the evaporation based on the Dalton type semi-empirical equations are approximately the same for both cases of the input data (Maitri and Irgason). The performance of the bulk aerodynamic method and semi-empirical equations was quantified by applying the Pearson correlation coefficient (*R*), the Nash-Sutcliffe index (*NSI*) and the s-sigma criteria (SSC). The bulk aerodynamic method gave the best fit to the EC method according to all criteria (Table

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5). The efficiency of the Dalton type semi-empirical equations is low: the correlation coefficient varied from 0.34 to 0.48, and both Nash-Sutcliffe efficiency index and s-sigma criteria indicated a low ability of the methods in estimations of the 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	0.96	–1.3	0.56	0.93	–1.6	0.75
Penman, 1948	0.34	–2.8	1.3	0.43	–2.5	1.2
Doorenbos and Pruitt, 1975	0.40	–2.5	1.2	0.48	–2.5	1.2
Odrova 1979	0.38	–4.2	1.8	0.46	–3.8	1.7

Figure 9 shows the daily time series of the evaporation estimated with the bulk aerodynamic and EC methods. The maximal discrepancies between the evaporation occur on those days when the wind speed exceeds 6 ms^{-1} (Fig. 5 c). On such days, the bulk aerodynamic method underestimates the daily evaporation up to 30 %. A possible reason is that the bulk method does not account for evaporation from spray droplets, which gets more efficient with increasing wind speed (Andreas, 1992).

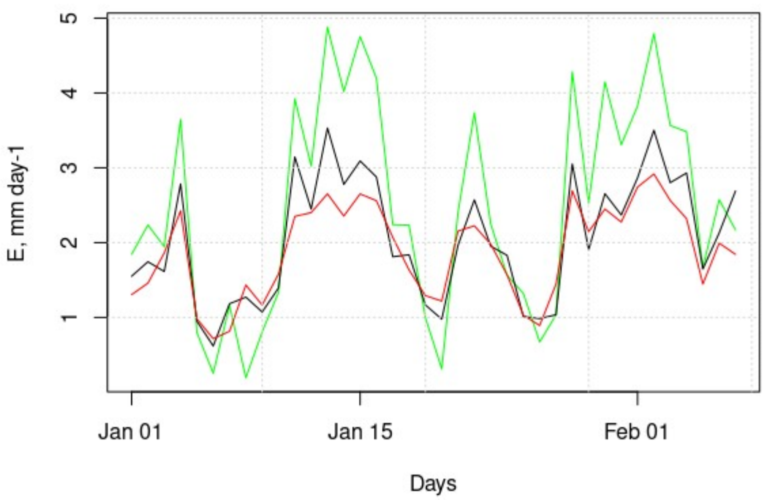

Figure 9: The daily evaporation evaluated applying the EC method (green) and the bulk aerodynamic method with two input data: measured at Maitri site (red) and at Irgason site (black).

5 Discussion

In water balance monitoring sites, the evaporation is practically measured with evaporation pans since the EC method requires specific equipment not always possible to deploy and operate. However, in the remote Antarctic continent, measurements by the evaporation pans or with the eddy covariance systems are difficult to carry out. Hence, the evaporation (sublimation) is usually estimated only indirectly on the basis of regular or campaign observations or numerical model experiments. Estimates of evaporation (sublimation) over the Antarctic areas have demonstrated a huge spatial variation (Thiery et al., 2012), and there are only a few studies of 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, it is the landlocked type lake, and its surface has decreased more than twice since late 1980s to early 2000s (from 4.0 x 10^3 to 2.0 x 10^3 m^2). The authors used 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 couple of weeks in December, 2006. The average daily evaporation was estimated to be 4.7 ± 0.8 mm day^{-1}. These estimates result in the loss of the liquid water at 40 ± 5 % of the total volume of the lake during the observational period. Although the lake studied by Borghini et al. (2013) differs from Lake Zub/Priyadarshini, the daily evaporation rates are of the same order of magnitude. One could expect a much larger evaporation from a landlocked lake than from a glacial one. The landlocked lakes in Antarctica are usually small endorheic ponds, which do not affect the surrounding land areas. The water surface temperature of the landlocked lakes rise up to 10-12 ºC, and it makes a bigger temperature contrast between the water surface temperature and ambient air temperature in the morning hours, and also results in intensive evaporation.

Shevnina and Kourzeneva (2017) used indirect methods to evaluate the daily evaporation for two glacial lakes (69° S) located in the Larsemann Hills oasis, East Antarctica. Both lakes (Lake Progress and Lake Nella/Scandrett) are of the epiglacial type, however they are much deeper and larger in volume than Lake Zub/Priyadarshini, and have a higher ice-covered fraction of the catchments. The thermal regime of these epiglacial 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 lower than the water surface temperature 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 the energy budget method and the semi-empirical equation after Odrova (1979), respectively. It was concluded that the daily evaporation over the epiglacial lakes is substantially underestimated by both indirect methods. Our results prove that the uncertainties of the semi-empirical equation after Odrova (1979) exceed 50 %. In our future study we will also use the energy balance method to estimate the evaporation over epiglacial lakes in Antarctica, and it allows evaluation of the uncertainties inherent also to this method.

Faucher et al. (2019) estimated the annual water balance (including the sublimation over the surface) for Lake Untersee (71° S), Dronning Maud Land, East Antarctica. Lake Undersee is the epiglacial type (not the landlocked type, as mentioned in Faucher et al. 2019), and it is perennially frozen year-round. These estimations of the sublimation over the lake surface are

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based on two years of in-situ measurements applying snow sticks. The authors concluded that the water losses from the ice covered surface of the lake varied from 400 to 750 mm year^{-1}. Therefore the daily evaporation from the lake surface is estimated to be approximately 1.1–2.1 mm day^{-1}, which is much less than that from Lake Zub/Priyadarsini in January, as one could expect in the case of a year-round frozen lake.

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. There the average daily evaporation in summer is 0.3 mm day^{-1}. To estimate how large the regional evaporation for the East Antarctic slope would be in case of accounting to the glacial lakes, 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 glacial lakes. In summertime, the areal fraction of ice-free glacial lakes over the East Antarctic slope (including the supraglacial lakes reported in Stokes et al. (2019)) reaches up to 6–8 %, and it may add up to 0.16–0.22 mm to the regional summertime evaporation over the margins of the East Antarctic slope.

The estimations of a time of water exchange and lake volume for the epiglacial lakes are sensitive to the uncertainties inherent to the methods applied to evaluate the evaporation (Shevnina et al., 2021). Our calculations yielded estimates of the uncertainties of the indirect methods. The bulk aerodynamic method underestimated the daily evaporation of over 30 % compared to the EC method, but it reached the best skill scores based on the efficiency indexes. The efficiency of Dalton type semi-empirical equations was low, and therefore we do not suggest those empirical equations to be applied in studies of the lake water balance. In our opinion, site-specific tuning of the Dalton type semi-empirical equations has potential to improve their efficiency.

6 Conclusions

This study was a step forward to develop the hydrological (water balance) to evaluate volume of the glacial lakes with estimates of summertime evaporation over an ice-free lake surface applying indirect methods, only needing as input a few hydrometeorological parameters monitored at selected sites (e.g., WMO stations). Our study focused on a glacial lake located in the Schirmacher oasis, Dronning Maud Land, East Antarctica. The results of the study suggested that the evaporation over the epiglacial Lake Zub/Priyadarsini in summer months is ca. 6–10 times higher than the amount of precipitation during the warm season. It confirms that evaporation/sublimation is an important process controlling water loss in the glacial lakes, and evaporation is a significant term of the water balance of the glacial lakes. Therefore, the summertime evaporation over lakes needs to be taken into account when predicting the volume of water in the glacial lakes located over the margins of the Antarctic ice sheet.

This study contributes with estimations of efficiency for the indirect methods applied to evaluate summertime evaporation over a lake surface. We suggest applying the bulk aerodynamic method to estimate evaporation over glacial lakes during the summer months because it demonstrated lower uncertainties than Dalton-type empirical equations. However, the underestimated mean evaporation rate based on the bulk method suggests that more attention is needed on the values of the

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turbulent transfer coefficients. We further stress the need for accurate surface temperature measurements in glacial lakes to serve studies on evaporation and a lake water budget.

In general, the evaporation results were not sensitive to differences in the meteorological data between Maitri and the Irgason site located at the lake shore. Hence, we suggest using the synoptic records at the nearest meteorological site Maitri in further water balance studies 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 glacial lakes (including evaporation) are closely connected to the lake 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 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 method has some errors and uncertainties associated with the nature of the measurement and the instrument system, therefore, the results need to 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), there are three methods to quantify the total random uncertainty for the eddy covariance method: the paired tower, 24 h differencing, and the model residual. In our study we apply the paired tower method 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 on the 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 the advantage that both instruments are 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 post-processed applying the algorithm given in Potes et al. (2017). It 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).

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

Figure A2 shows a scatter plot between 30-minute evaporation evaluated after the measurements of two instruments during the intercomparison campaign that took place in Alqueva reservoir. The correlation coefficient between the evaporation calculated after two Irgason is over 0.98, and it 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 30-minute evaporation, 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 to obtain an estimate of the random instrument error of 7.0 %. This value is below another studies presented by several authors, namely: Eugster et al. (1997), that used the same approach of the paired towers in Alaska tundra, and obtained 9 % for latent heat flux; Finkelstein and Sims (2001), that present a value between 14 and 35 % for latent heat flux in forest and agricultural sites; Salesky et al. (2012), that found typical errors of 10 % for the heat flux.

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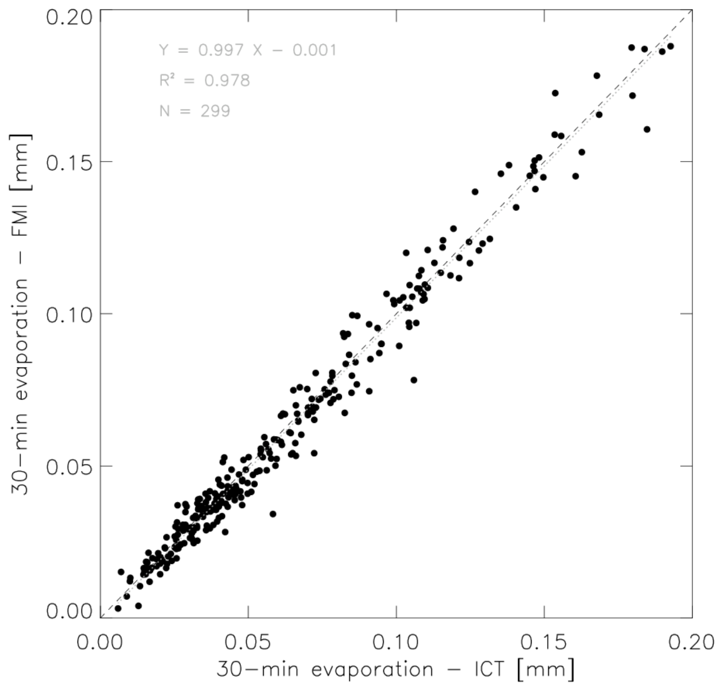

465 **Figure A2: Scatter plot between 30-minute evaporation from both instruments: Y-axis is the values estimated after the measurements by the Irgason of FMI, and X-axis is the values after the measurements of the Irgason of ICT.**

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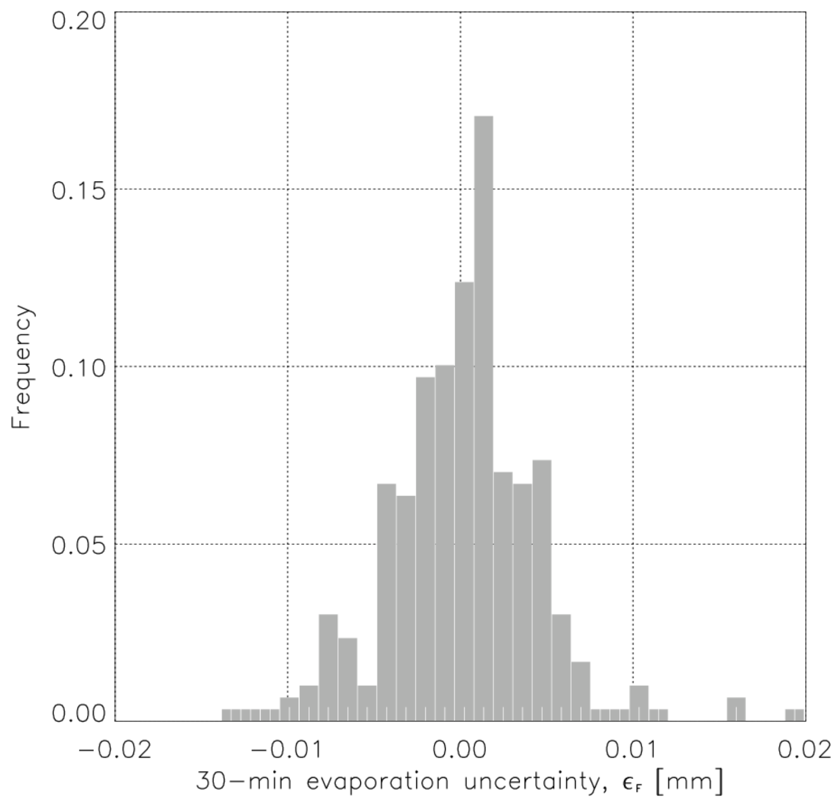

Figure A3: Frequency distribution of the 30-minute evaporation random instrument uncertainty (ε_F).

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Supplement. ES attached the calculation of the evaporation with the semi-empirical equations (EvaporationZub_Irgason.csv) and code used to evaluate the estimates of the uncertanties inherent 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.txt). PD have attached meteorological data measured at the Maitry 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, he carried out the calculations applying the EC method (including the intercalibration campaign). TV contributed with the estimations of evaporation applying the bulk aerodynamic method. PD and PKT contributed with the analysis of the meteorological observations at Maitri site. TN contributed with analyses of evaporation based on ERA5. All authors contributed to writing of the manuscript.

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

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