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.

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).

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 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– of 1969-1978 (Klokov, 1979). Estimations of the area forPicard et al. (2007) evaluated the melting zone in Antarctica are also available from thearea over the continent on the basis of microwave remote sensors for the summers in the period 1979/80– 2005/06; the melting zone has expanded 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 (Picard during the last 27 years. Stokes et al., 2007). (2019) used remote sensing data to detect water bodies over

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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).

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, a modelling approach has modelling approaches have 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 local effects of climate warming to lake physiographic parameters. The water balance equation of a lake particularly allows estimating the volume of allows estimations of changes in the lake from known volume due to inflow and outflow terms (precipitation, evaporation, surface/subsurface inflow/outflow runoff, water withdrawal) to be measured or modelled. Different processes in Antarctica 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 the lakes (and their water budget) both glacial and landlocked types of lakes are sensitive to uncertainties inherent into 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.

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 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, weatherclimate 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 (Fig. 1 b); its total area is. 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).
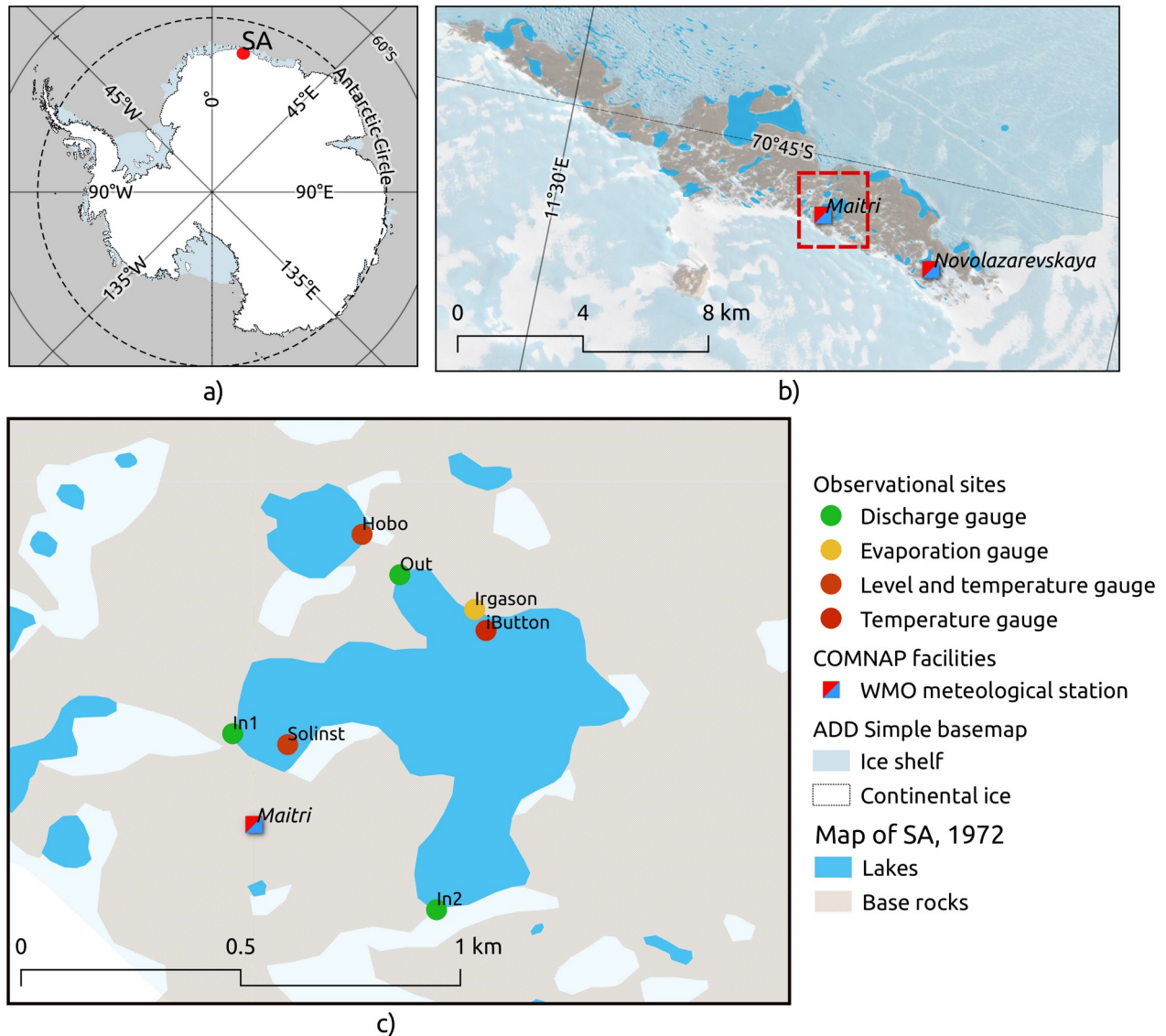
Figure 1. The lakes in the : The study region: (a) Location of the Schirmacher oasis (SA) in Antarctica; (b; (b) the glacial lakes in the coast of the Dronning Maud Land; (c) the lakes in SA (after Map of SA, 1972) with Landsat Image Mosaic of Antarctica, LIMA given as the background; (c) the temporal observational network in the catchment of Lake Zub/Priyadarshini. .

The climate of the Schirmacher oasis is characterized by low air humidity and temperature and a , 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). Two meteorological sites operateThere are two meteorological observation sites operating in the Schirmacher oasis. The (Fig. 1 c). The meteorological observations were

started in 1961 at the Novolazarevskaya (Novo) meteorological site (70°46′36″S, 11°49′21″ E, 119 m asl, World~~elevation, Word~~ Meteorological Organization (WMO) number 89512). The ~~, 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, 137 m asl~~130 m elevation~~, 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; ~~, and~~ their measurements are performed~~done~~ according to standards of~~by~~ WMO (Turner and Pendlebury 2004). Table 1 shows weather conditions during the austral summer 2017–2018 and averaged over the period 1961–2020~~climatology (1961–2020) of the Schimacher oasis~~ according to the observations at the Novo site (the data are provided~~given~~ 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

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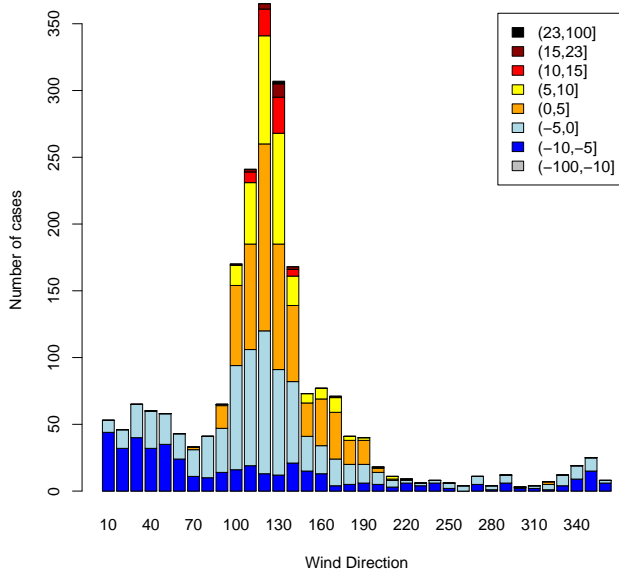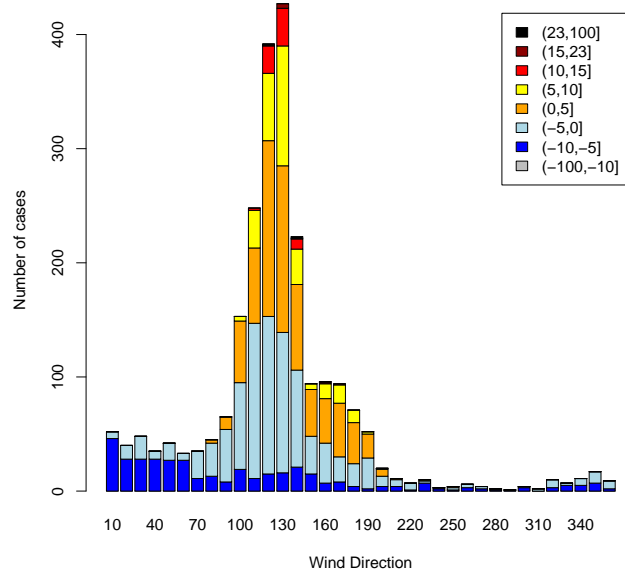
Figure 2: Wind direction and frequency of wind speed anomalies according to the observations at Novo meteorological site: (a) December; (b) January.

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 For the summer sea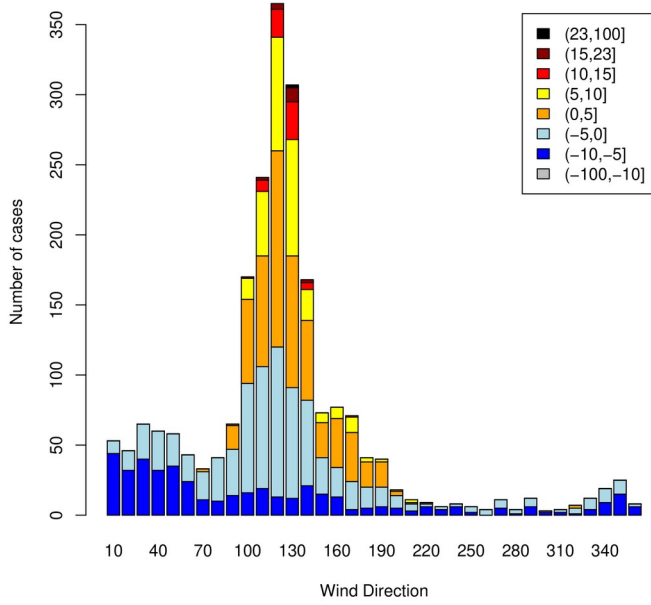son 2017–2018, the observations at the Maitri site were very similar to those at the Novo site, with the Novo site (Fig. 3). The correlation coefficient between the daily series of the air temperature, relative humidity and wind speed varyingvary from 0.95 to 0.98. According to the Maitri meteorologicalmeteo 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.

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

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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)

(a)

(b)

(c)

(d)

More than 300 lakes are mapped in the oasis (Fig. 1 be), 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 physiography of the lakes lake physiography is available from bathymetric surveys for on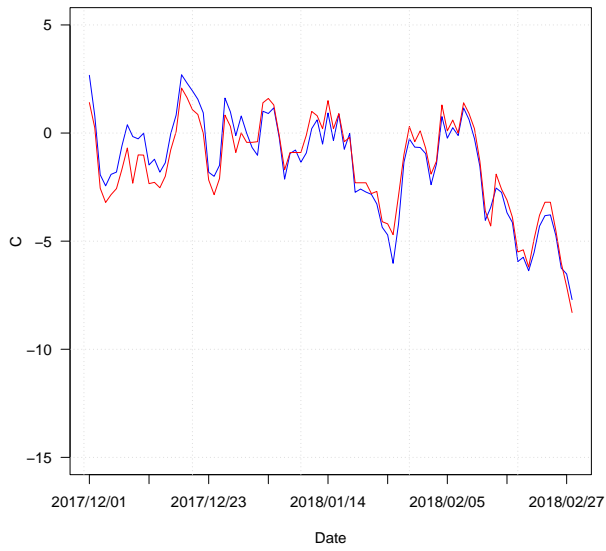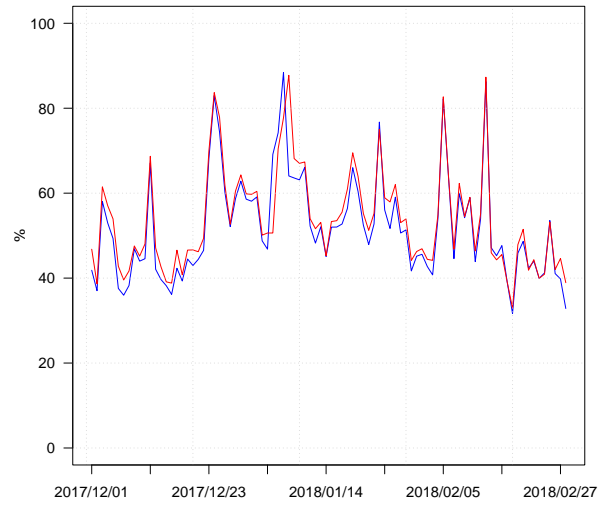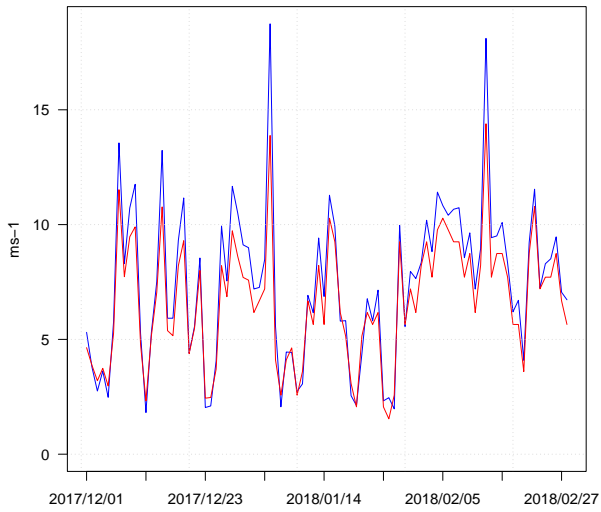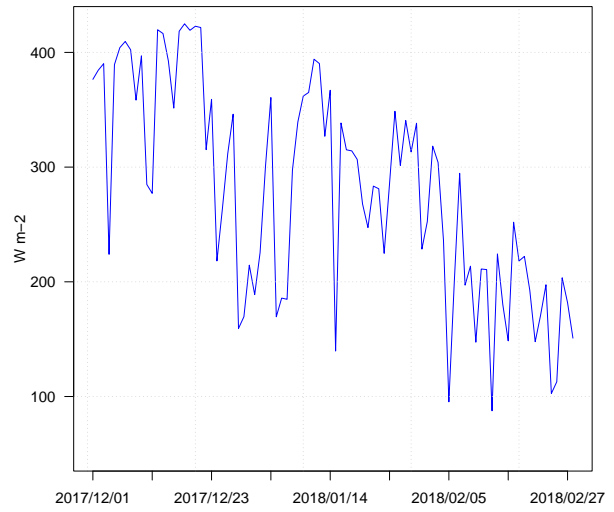ly the largest lakes (Simonov and Fedotov, 1964; Loopman et al., 1988; Sokratova, 2011; Asthana et al., 2019). The hydrological cycle and changes in the volume in these lakes are modulated by the seasonal weather cycle (Sokratova, 2011; Asthana catchments of the epiglacial lakes include different portions 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 km² in the region covering over two grid cells in the ERA5 (the shadowed box in Fig. 1 b).

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 x10³ m², its volume is over 10.0 x10³ m³, 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).

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 x10³ m², and its volume is over 10.0 x10³ m³ (Khare et al., 2008).~~

3. Data and Methods

~~3 Field experiment, data and methods~~

245 ### 3.1 Data~~Field experiment~~

We collected the hydrological and special meteorological observations needed to evaluate ~~During the field experiment in January–February, 2018, we collected the measurements needed for evaluation of~~ the water balance terms of Lake Zub/Priyadarshini in the field experiment of 2017–2018~~the lake including the evaporation over the lake surface during the ice free period~~. The temporal hydrological ~~observational~~ network included water level/temperature gauges, water

250 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. ~~4 a).~~ The evaporation gauge was a flux tower equipped with the~~an~~ Irgason EC measurement device by Campbell Scientific (user~~Instruction~~ manual available at https://s.campbellsci.com/documents/ca/manuals/irgason_man.pdf, last access 09.07.2021). The Irgason comprises ~~consists of~~ a 3D sonic anemometer and two gas analyzers~~analysers~~ measuring CO_2 and ~~/~~H_2O concentrations. It was deployed on the

255 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~~to~~ the shoreline of Lake Zub/Priyadarshini for the period ~~of~~ 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 ~~The~~ experiment lasted for 38 days, and the meteorological parameters (air temperature, wind speed and relative humidity) were measured

260 simultaneously at the Maitri meteo site and at the evaporation gauge located on the lake shore (Irgason in Fig. 1 c~~4 a~~). The data gathered by the various sensors cover observational periods lasting from 14 to 45 days (Table 2).~~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).~~

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; H_2O 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

13

	119.5			
Solinst	123	=	01.01.2018 – 15.12.2018	
iButton		=	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.

265 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

270 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

275 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.

a)

b)

c)
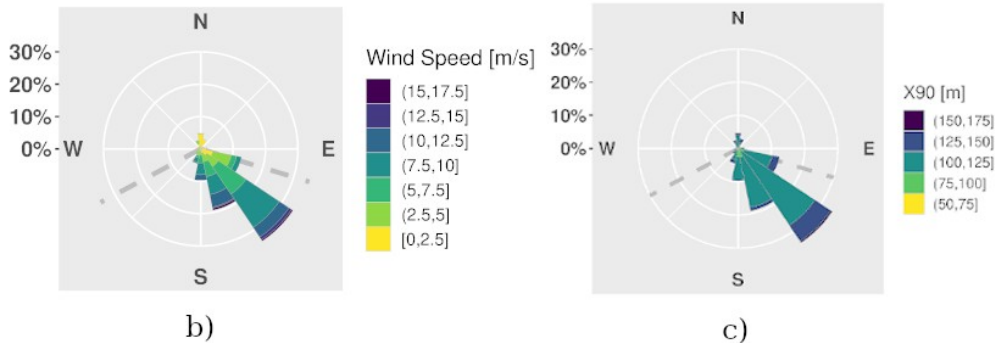
Figure <u>3: 4:</u> The experiment on the coast of Lake Zub/Priyadarshini: ~~January-February, 2018:~~ (a) ~~meteorological and hydrological observational network; (b)~~ Irgason deployed on the lake shore (06.01.2018); (<u>b</u>~~c~~) wind speed and direction measured at <u>the Irgason site, the</u> ~~Irason site,~~ dashed line indicates the footprint wind sector<u>; (c) the footprint length estimate (X90)</u>.

<u>The measurements of the water temperature were needed to allow the estimation of the evaporation after the Dalton type</u>
<u>empirical equations. Therefore, we measured the water temperature over the surface of the lake with three sensors installed</u>

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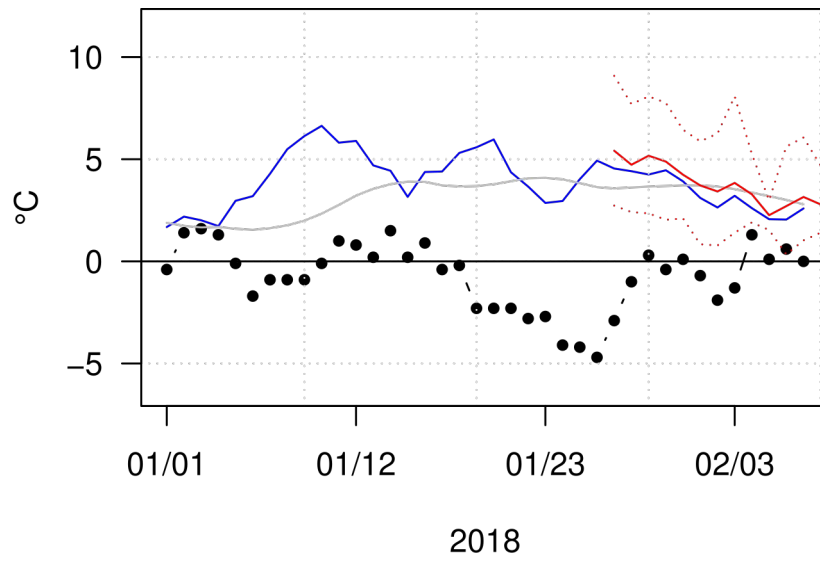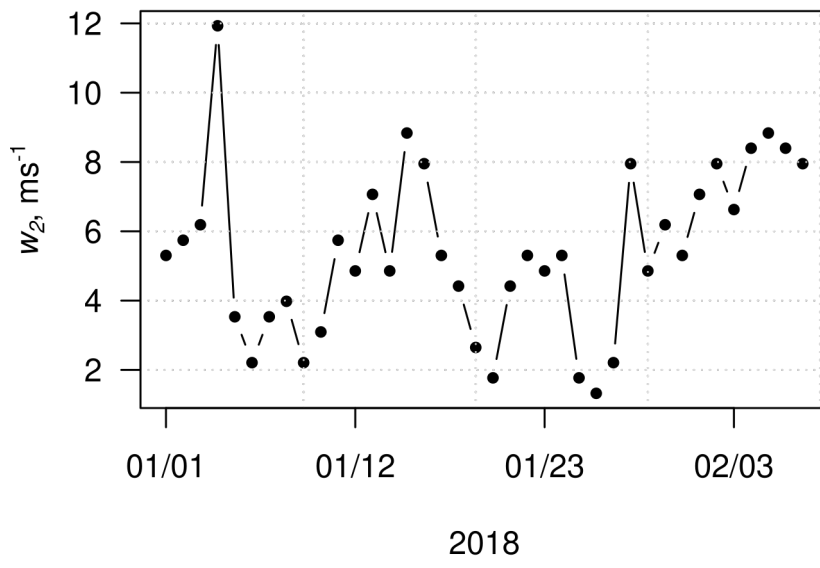
Figure 4: Daily time series of: (a) the lake surface water temperature measured by the Hobo (blue), iButton (red) and Solinst (grey), and the air temperature measured at the Maitri site (black); (b) the 2-meter wind speed estimated with

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: The 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).

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 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; H2O concentration, g/m^3; 3D	01.01.2018 – 07.02.2018

|		
	wind speed, ms^{-1}	
Hobo	Water temperature, ºC	30.12.2017 – 09.02.2018
Solinst	–	01.01.2018 – 15.12.2018
iButton	–	27.01.2018 – 09.02.2018
Maitri site	Air temperature, ºC; wind speed, ms^{-1}	01.12.2017 – 28.02.2018

3.2 Methods~~Data~~

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: In 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).

~~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).~~
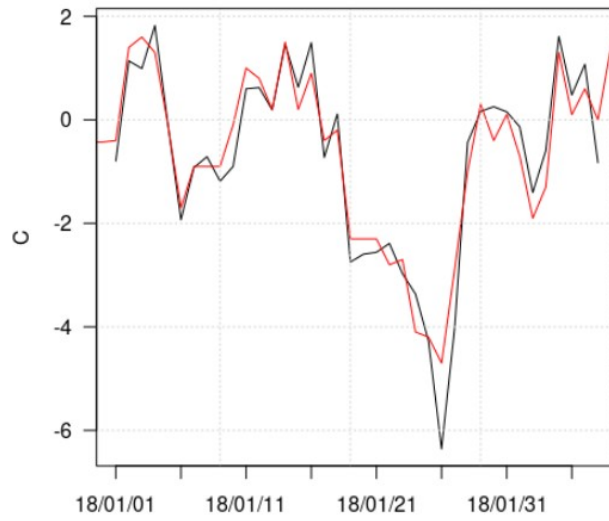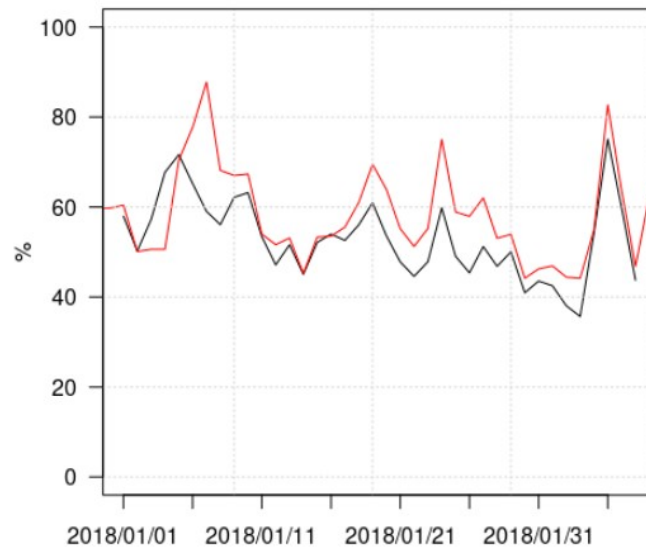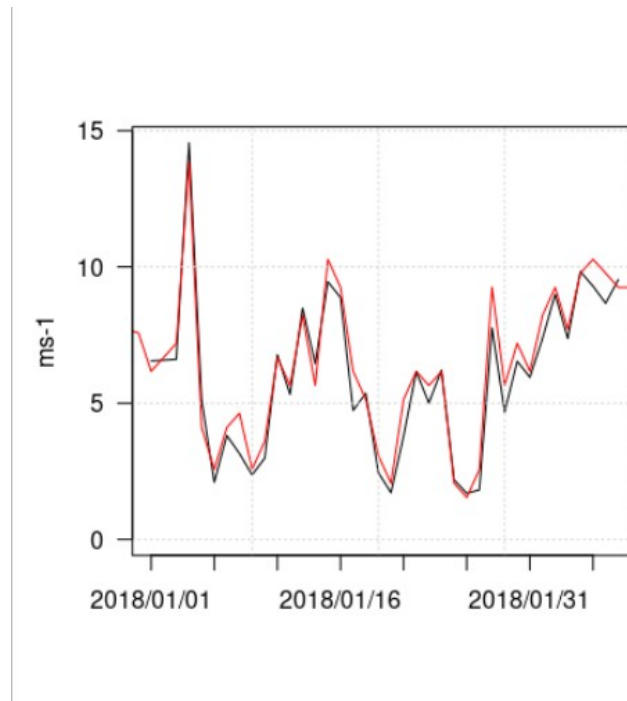
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(c)

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

We also filtered the data outside the footprint, which covered the winds~~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 direction ranging from 105 to 240° (Fig. 3 b), to account only for ~~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 excluded ~~, we also filtered the data outside the footprint, which covered the winds with the direction ranging from 105 to 240° (Fig. 4 c). Only~~ 18 % of the total measurements ~~were excluded~~ from further consideration after three filtering steps~~steps filtering~~, and these gaps were replaced~~we replaced these values~~ 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

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395 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
400 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
405 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 ~~In the bulk aerodynamic method, 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.,~~ie.~~ ice or water)~~,~~ and the air, as well as the factors that affect the intensity of the turbulent exchange:
410 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 ~~was calculated as follows~~:

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

where, E is the evaporation (kg s^{-1}); ~~ρ~~ 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
415 speed. The subscript z refers to the observation height (here 2 meters). We ~~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) for the turbulent transfer coefficient for moisture under neutral stratification (C_{EzN}). This~~. 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 stratification is not always neutral, so we took ~~value of~~ C_{Ez}~~, taking~~ into
420 account the effects of stratification on the turbulent transfer coefficient C_{Ez}~~thermal stratification, was calculated from the neutral value~~ as follows:

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

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

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425 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~~m~~, and converted to our observation height of 2 meters~~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.

430 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~~the height of 2 m~~:

$$E = C(e_s - e_2) \tag{3}$$

where, E is daily evaporation, mm day^{-1}; e_s is the water vapor saturation pressure; e_2~~e_{200}~~ is the water vapor pressure at 2 meters~~m~~ height; C is a coefficient (or a function) depending ~~depend~~ on meteorological conditions (or a linear wind function

435 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).~~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:~~

440 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:

$$E = 0.26(1 + 0.54 w_2)(e_s - e_2) \tag{4}$$

$$E = 0.26(1 + 0.86 w_2)(e_s - e_2) \tag{5}$$

$$E = 0.14(1 + 0.72 w_2)(e_s - e_2) \tag{6}$$

445 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

450 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

455 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

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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:

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

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):

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

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

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.

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.
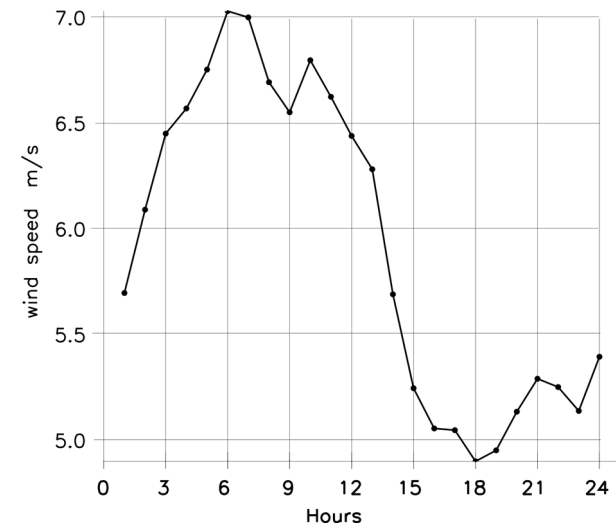
4 Results

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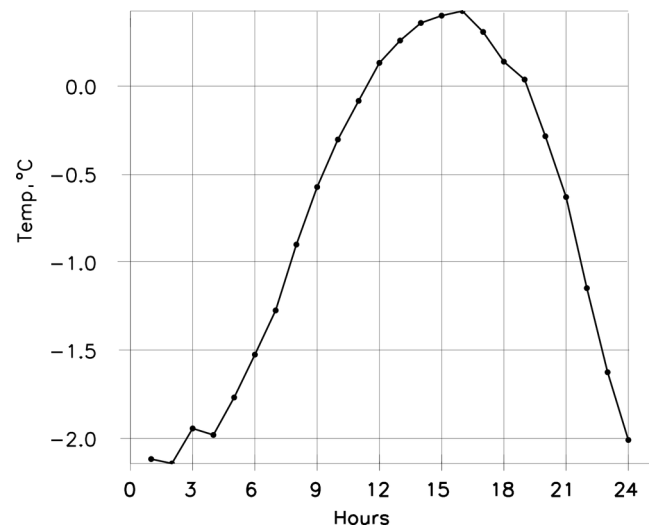
Variable name	Site: Irgason	Site: Maitri	Site: Hobo	Site: iButton**	Site: Solinst
Wind speed, ms^{-1}	1.7 / 6.0 / 14.6*	1.5 / 6.4 / 13.9	–	–	–
Wind direction, °	/ 150 /	/ 151 /	–	–	–
Relative humidity, (%)	28 / 42 / 56	44 / 58 / 88	–	–	–
Air temperature, C	-6.4 / -0.8 / 1.8	-4.7 / -0.7 / 1.6	–	–	–
Water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

4.2 Evaporation

We considered the direct EC~~eddy covariance~~ 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). ~~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 1.5~~0.05~~ to 5.0 mm day⁻¹ with the average equals ~~mean value equal~~ to 3.0 mm

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

4.2 Evaporation

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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: By 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 38 days, it results in 114 mm of water evaporating~~ over the period of the field experiment is 94 mm if we simply excluded whole gaps in the 30-minute series.~~lake surface.~~

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).

~~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 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

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| 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.

a)

b)

c)

d)

~~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 km². 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 km² (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.~~

~~(a)~~   ~~(b)~~
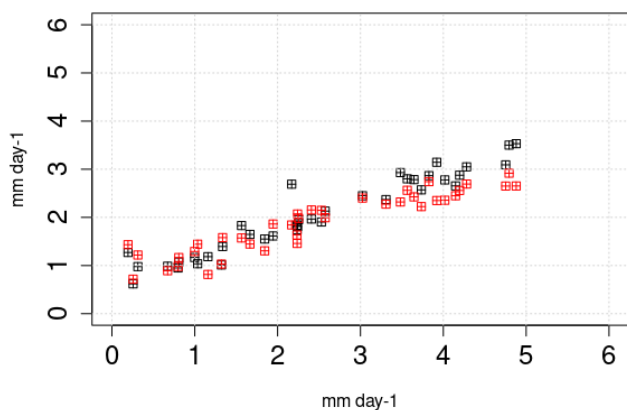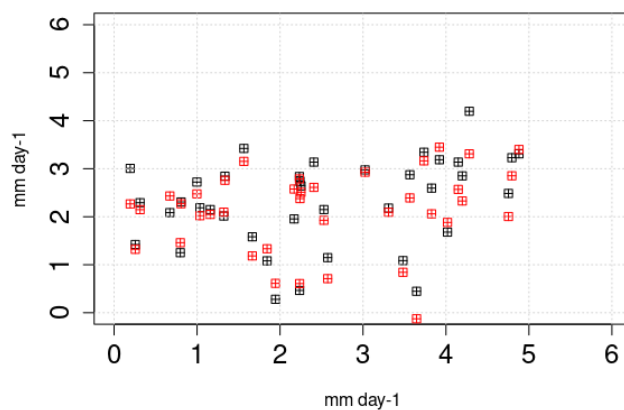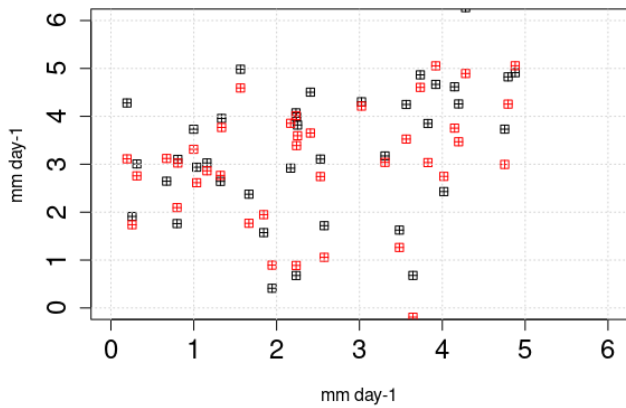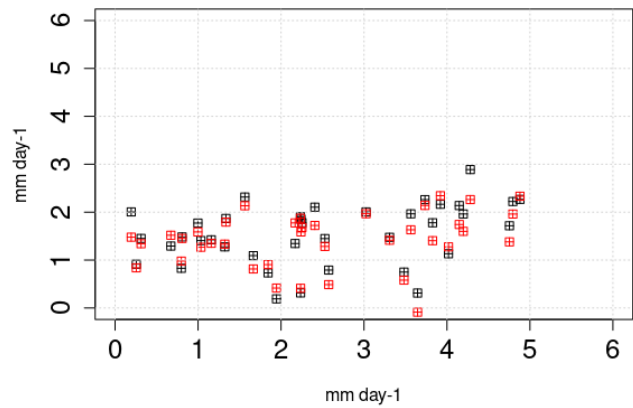
Figure 58: Scatter plots of the daily evaporation estimated with the indirect methods (Y-axis) against the direct EC method (X-axis): (a) the bulk- aerodynamic; (b) Penman; (c) Doorenbos and Pruitt; (de) Odrova. The red dots indicate the estimates of the evaporation with the meteorological parameters measured at WMO synoptic site Maitri, which is the nearest to Lake Zub/Priyadarshini. The black dots indicateindicated those estimates of the evaporation performeddone with the meteorological parameters measured at the lake shore (Irgasin site)Irgason site.

The bulk-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 (bold notation in Table 5). As one can expect, the The-efficiency of the Dalton type semi-empirical equations is poor: Thelow: the correlation coefficient varied from 0.1234 to 0.3448, and both *NSS and SSCNash-Sutcliffe efficiency index and s-sigma* criteria indicated a low ability of the methods to estimate the dailyin 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	0.87	−0.1	1.1	0.88	−0.5	1.2

Methods	R	NSI	SSC	R	NSI	SSC
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).

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

600 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).
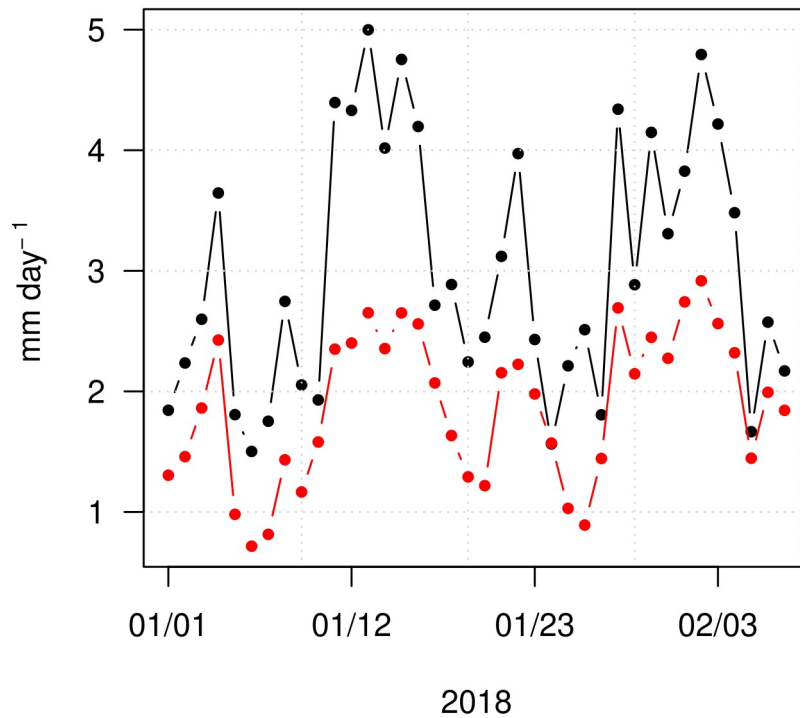
4.2 Empirical models

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 $a + b_1 w_2 + b_2 (e_s - e_2)$, where $(e_s - e_2)$ 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: The 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

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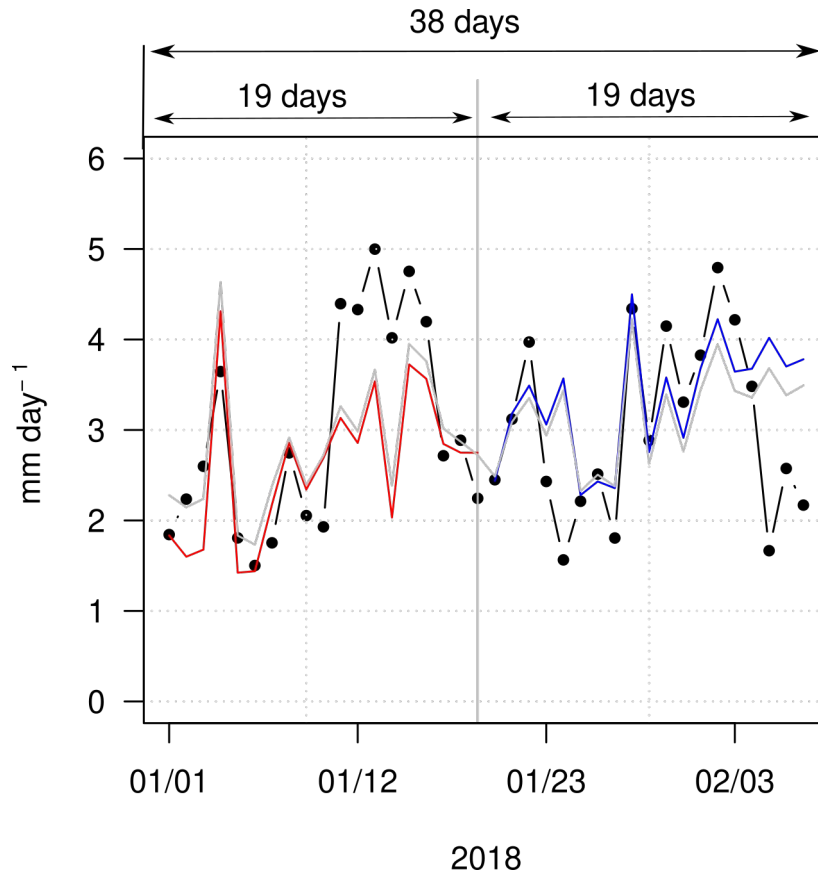
Figure 7. The daily series of the evaporation evaluated after applying the direct EC method (black) and applying the linear regression with the empirical coefficients estimated from data collected during various periods: 01.01.2018–07.02.2018 (grey), 01.01.2018–19.01.2018 (blue) and 20.01.2018–07.02.2018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

Table 6 shows the estimates of the empirical coefficients in the linear relationship $a + b_1 w_2 + b_2 (e_s - e_2)$, 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.

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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 $\sqrt{\sum_1^n \left(E_{EC}-E_{mod}\right)^2/n}$; 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 60–130º), 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 60–130º. 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 60–130º (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 60–130º and when it was 240–350º.

Geostrophic wind dir.	Evaporation (mm day^{-1})	w_2 (m s^{-1})	Q_2 (g kg^{-1})	w_t (ºC)	t_2 (ºC)
60–130º	3.1	6.9	2.0	3.6	−0.2
240–350º	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.

~~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

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.

690 ~~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~~

695 ~~(Thiery et al., 2012), and there are only a few studies of evaporation over the lakes located in Antarctica.~~

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

700 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 from the ~~since~~ late 1980s to the early 2000s (from 4.0 x 10^3 to 2.0 x 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~~authors used~~ the semi-empirical equation given in Shuttleworth (1993) to calculate the evaporation from the

705 ice-free water surface with data on the water temperature, air temperature, and wind speed collected during a few ~~couple of~~ weeks in December~~,~~ 2006. The mean~~average~~ daily evaporation was estimated to be 4.7 ± 0.8 mm day^{-1}. These estimates resulted~~result~~ in the loss of the liquid water at 40 ± 5 % of the total volume of the lake during the observational period. The ~~Although the~~ lake studied by Borghini et al. (2013) differed~~differs~~ from Lake Zub/Priyadarshini, yet the daily evaporation rates are of the same order of magnitude, and one can even ~~. One could~~ expect a much larger evaporation over the surface

710 ~~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 than over the glacial lakes.~~rise up to 10-12 °C, 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 two indirect methods to evaluate the daily evaporation of two lakes ~~for two glacial~~

715 ~~lakes (69° S)~~ located in the Larsemann Hills oasis, East Antarctica (69° S). ~~. Both lakes (~~Lake Progress and Lake Nella/Scandrett~~)~~ are of the glacial type; however,~~epiglacial 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~~have a higher ice-covered fraction of the catchments~~. The thermal regime of these glacial~~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, which is ~~lower~~

720 than the water temperature over the surface ~~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 applying the energy budget method (Mironov et al., 2005) and the semi-empirical equation after applying Odrova (1979), respectively. It is~~was~~ concluded that the daily evaporation over

the glacialepiglacial lakes is substantially 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.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) evaluated the annual water budget for Lake Untersee, the Dronning Maud Land, East Antarctica (71º 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.
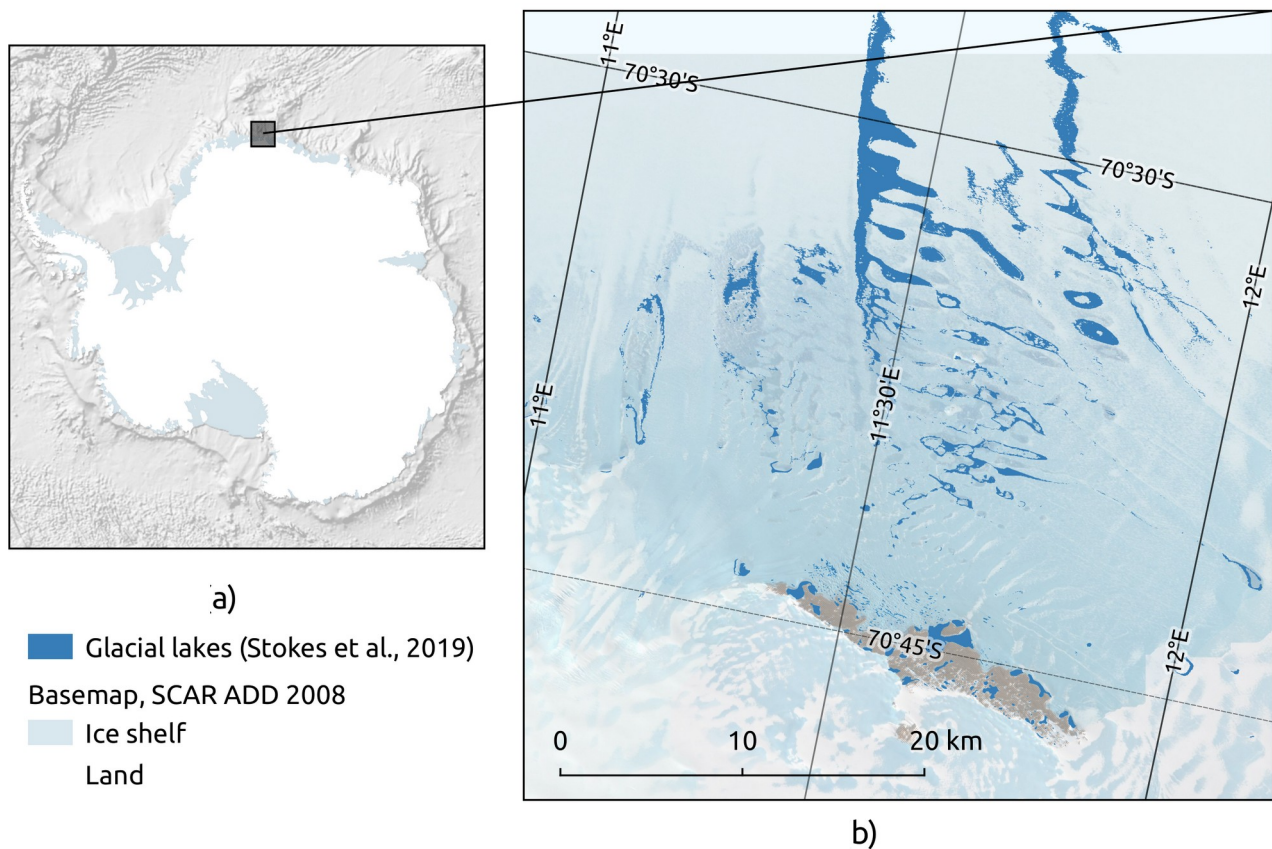
Figure 8. The glacial lakes over the surface of ice shelf in the vicinity of the Scirmacher oasis, East Antarctica.

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.

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

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Faucher et al. 2019), and it is perennially frozen year-round. These estimations of the sublimation over the lake surface are 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. The There 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 . To estimate how large the regional evaporation for 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 would be in case of accounting to 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 , 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 In summertime, the areal fraction of ice-free glacial lakes 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 suggested more comprehensive research to better understand the role of the glacial lakes on the surface-atmosphere moisture exchange and surface radiative budget (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 ice cover in the polar regionsEast 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 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).

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 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.

The In general, the evaporation results were not sensitive to differences in the data collected at the meteorological site nearest to the lake meteorological data between Maitri and the Irgason site located onat the lake shore. Hence, we suggest using the synoptic records at the nearest meteorological site Maitri to evaluate the evaporation over the surface 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 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).

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

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Figure A2 shows a scatter plot between <u>a</u> 30-minute evaporation evaluated after the measurements of two instruments during the intercomparison campaign that <u>occurred</u> ~~took place~~ in Alqueva reservoir. The correlation coefficient between the evaporation calculated after two Irgason is over 0.98, <u>which</u> ~~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

860 intercomparison campaign (see the Eq. 9 from Dragoni et al., 2007). The random instrument error in <u>the</u> 30-minute evaporation <u>is</u> ~~,~~ 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 <u>us</u> to obtain an estimate of the random instrument error of 7.0 %. This value is below <u>other</u>~~another~~ studies presented by several authors, namely<u>,</u>~~.~~ Eugster et al. (1997), <u>whom</u>~~that~~ used the same approach of the paired towers in <u>Alaskan tundra</u>~~Alaska tundra,~~ and obtained 9 % for latent heat flux; Finkelstein and

865 Sims (2001), <u>who presented</u>~~that present~~ a value between 14 and 35 % for latent heat flux in forest and agricultural sites; <u>and</u> Salesky et al. (2012), <u>who</u>~~that~~ found typical errors of 10 % for the heat flux.

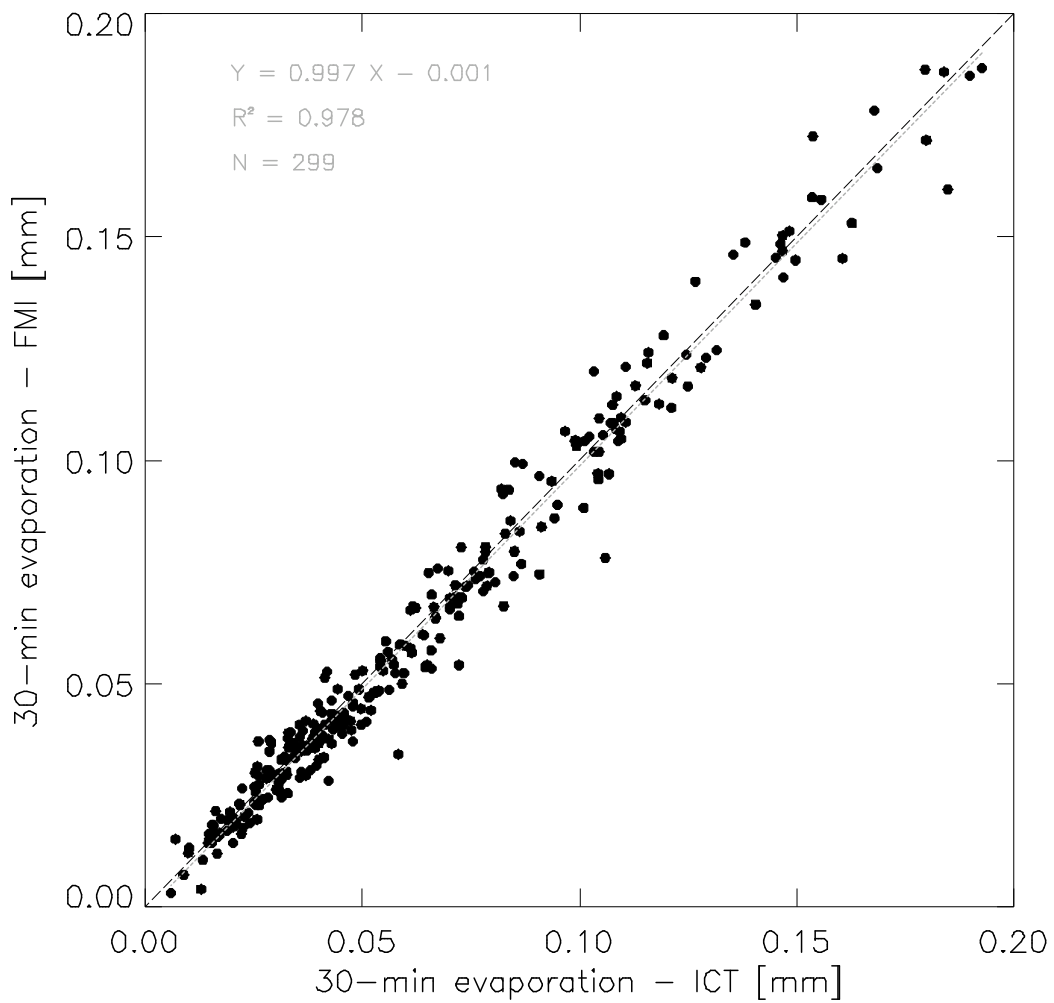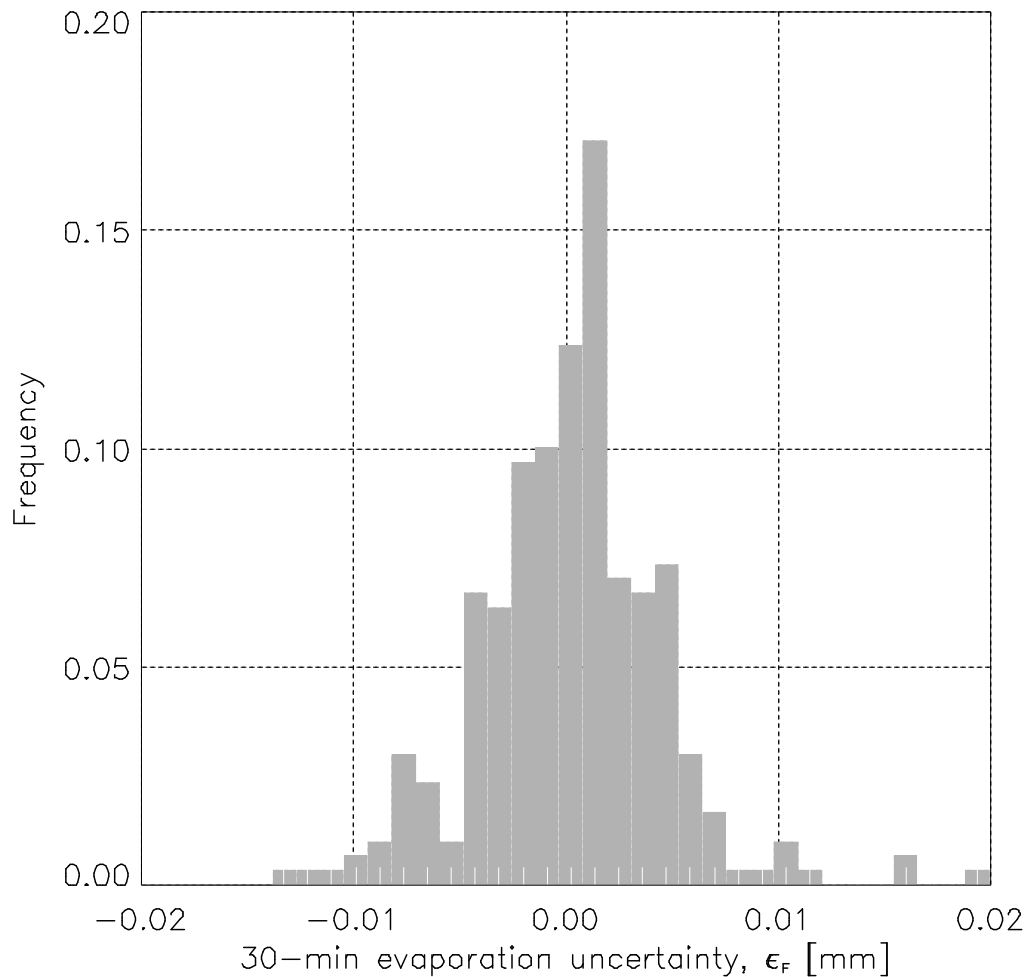**Figure A2: Scatter plot between 30-minute evaporation from both instruments: Y-axis is the values estimated after the measurements by the FMI Irgason~~Irgason of FMI~~, and X-axis is the values after the measurements of the ICT Irgason~~Irgason of ICT~~.**

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

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885 **Supplement.** ES attached the calculation of the evaporation with the semi-empirical equations (Dalton_equations_resultsEvaporationZub_Irgason.csv) and code used to evaluate the estimates of the uncertainties inherent in 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 Irgason input.txt and Bulk method results Maitri input.txt.txt). PD have attached meteorological 890 data measured at the MaitriMaitry 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:

895 **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, he 900 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 PD and PKT contributed with analyses of evaporation based on ERA5. TV and TN performed the analysis of the impact of the katabatic winds. PD and PKT meteorological observations at Maitri site. TN contributed with the analysis of the meteorological observations at Maitri siteanalyses of evaporation based on ERA5. All authors contributed to writing of the manuscript.

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

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