Evaporation over epiglacial lakes: the case of Lake Zub/Priyadarshini, the Schirmacher oasis, East Antarctica.

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Abstract. Climate warming fasts melting of the ice -sheet, and the melted water is accumulated in numerous glacial lakes connected by ephemeral river network. Water cycle of these glacial lakes is not well known, and this study suggested first evaluations of the evaporation over the glacial lake located in the Schirmacher oasis (70° 45′ 30″ S, 11° 38′ 40″ E), the Droning Maud Land, East Antactica. Lake Zub/Priyadarshini is a typical lake of epiglacial type with low fraction of ice cover in its catchement area. The lake is ice free during almost two months in summer (December-February). We evaluated the evaporation over the ice free surface of Lake Zub/Priyadarshini various methods including the eddy covariance, the stability parameters, the energy budget and semi-empirical equations. The evaporation was estimated with the data collected during the field experiment in December–February, 2017–2018.

We considered the eddy covariance as most accurate method providing the reference estimations of the evaporation over the lake surface. It suggest the mean daily evaporation of over 3.0 mm day^{-1}. The field experiment lasts 38 days, and during this period almost 114 mm of water (over XX% of the lake volume) is evaporated.

We used the ERA5 reanalyse to evaluate the evaporation with the energy budget method form the data extracted in the grid point nearest to Novolazarevskay station. The daily evaporation rate estimated is over 0.6 mm day^{-1} for the summer 2017–2018. The ERA5 is underestimated the summer evaporation rate due to the coarse spatial resolution.

The bulk-aerodynamic method:

Most of the semi-empirical equations tend to underestimate the daily evaporation over the ice free surface of the lake (1.6–2.4 mm day^{-1}). Then, we estimated the empirical coefficients in the Dalton type equation from the measurements on the air temperature, wind speed and waer surface temperature. The verivication of the empirical coefficents are done by the cross-validation with the data colleted with 38 days of the field experiment.

We found, that the summer evaporation over ice free surface of the epiglacial lakes exceeds the summer precipitation by a factor of ca. 6–10 times. The evaporation is [a significant/ not significant] term of the water balance of the epiglacial lakes with low fraction of ice ccover in their catchments.

1 Introduction

Cold, dry and windy weather conditions leads to specific balance of liquid, vapour and solid phases of water in the polar regions including Antarctica. With increasing the near surface air temperature, liquid water is going to be more presented over the margins of the Antarctic ice sheet due to enhanced transition of water from solid phase (snow/ice) to liquid phase. Melted water accumulates in population of glacial lakes. These lakes may appear over a surface of ice-sheet (supra- glacial type), on a contract with an ice-sheet (epi- / pro-) glacial type), and inside the ice-sheet (sub-glacial type). Recently, remote sensors and geophysical surveys report a great amount of the glacial lakes both in Greenland and Antarctic ice-sheets. The glacial lakes are connected by ephemeral streams, which may be quickly developed in warm seasons. connected by ephemeral streams into hydrological network existing on the surface/inside of the continental ice sheet. Bell et al. (2018) notice that processes driven the meltwater production, the accumulation and water runoff are among poorly studied in Antarctica. This study contributes to the knowledge of the water balance of the glacial lakes located in the Schirmacher oasis, East Antarctica.

The glacial lakes appear inside the Antarctic ice sheet (subglacial type), over its surface (supraglacial type), or they are connected to the continental of shelf ice sheets (epiglacial type or epishelph type). The lakes of a land-locked type occupy local relief depression over deglaciated areas named as oases (Holgson, 2012). Various changes in the volume and lake surface are observed during last a couple of decades on the glacial lakes: big numbers of the supraglacial lakes are clearly detectable with remote sensing methods (Stokes et al., 2019); the lake volume increases in many epiglacial lakes located in the Dry Valley, West Antarctica (Foremann et al., 2004) and the Larsemann Hills, East Antarctica (Boronina et al., 2020). Many land-locked lakes are decrease in their volume and area in the ice free oases (Shevnina and Kourzeneva, 2017; Borgini et al., 2008). To better evaluate the amount of liquid water accumulated in these lakes, it is important to study their thermal regime closely connecting to a lake water balance. Shevnina et al. (2020) suggest to model the water balance of the lakes depending on their type because different mechanisms of water exchange in the epiglacial and land-locked lakes. The authors conclude that estimates of the water transport scale depend on the uncertainties inherent the methods evaluating evaporation over ice covered/ice free surface for both types of the lakes.

In most Antarctic studies, the evaporation over the surface of the lakes are evaluate after indirect methods (models) including the energy budget (Dhote et al., 2020; Faucher et al., 2019) or the semi-empirical equations (Shevnina and Kourzeneva, 2017; Borghini et al., 2013). This study contribute to better understanding the uncertainties the indirect methods used to evaluate the evaporation. The eddy covariance (EC) method (Burba et al., 2016) was used as a reference in the errors analysis because it provides the evaporation with the best accuracy (Tanny et al., 2008). The EC technique has been introduced to provide measurements of the turbulent heat fluxes over lakes for more than 30 years (Erkkilä et al., 2018; Mammarella et al., 2015; Aubinet et al., 2012; Beyrich et al., 2006; Blanken et al., 2000; Stannard and Rosenberry, 1991). However, the direct measurements of the evaporation over the ice covered and open surface of the polar lakes are rare.

Thiery et al., (2012) suggest that the evaporation (sublimation) over ice/snow covered areas show “a tremendous spatial variation” in estimates, which are obtained with various methods. Even in the continental interior, the sublimation over the snow cover may take up to 23 % of total precipitation (Gorodetskaya et al., 2015). Faucher et al. (2019) conclude that water losses from the ice covered surface of the lake varied from

400 to 750 mm yr^{-1}, these results are based on two year observations collected on Lake Undersee, Dronning Maud Land, East Antarctica. This amount of sublimation is much more than annual amount of precipitation observed in this region (Andersen et al., 2015). It should be noted, that Lake Undersee is the epiglacial type (not the land-locked lakes as it given in Faucher et al. 2019).

During the ice free season, evaporation is the main process controlling water losses of from many land-locked lakes located in the Larsemann oasis, Princess Elizabeth Land, East Antarctica (Shevnina and Kourzeneva, 2017). The authors evaluated the evaporation over the surface of five lakes with two indirect methods: the lake model FLake after Mironov et al. (2005) and after the semi-empirical equation Odrova (1979). The daily values differs of over 20–30 % for the evaporation estimated after these two methods, and direct measurements are needed to proof the estimates. Huang et al. (2019) show that evaporation (sublimation) over ice covered surface is much larger than precipitation for the land-locked lake located in the Tibetan Plato. These studies show that the role of evaporation over ice/snow/water surface in water balance may be underestimated in the cold climate areas, where the low air temperatures and ice covered surface block main sources of water vapour (Tietavainen and Vihma, 2007). Therefore, it is important to understand the uncertainties of the indirect methods used to estimate evaporation over ice free/ ice covered glacial lakes. This study aims to evaluate the evaporation over ice free surface of the epi- glacial lake located in the Schimacher oasis, Dronning Maud Land, East Antarctica. We applied various methods to estimate the evaporation over Lake Zub/Priyadarshini, which is among the biggest lakes in the region. We also evaluated the evaporation from the ERA5 reanalysis.

2 The Schirmacher oasis

The Schirmacher oasis (70° 45′ 30″ S, 11° 38′ 40″ E) is located approximately in 80 km from the coast of Lazarev Sea, Queen Maud Land, East Antarctica. The oasis is the ice free area elongated in a narrow strip around 17 km long and 3 km wide in West–Northwest to East–North-East (Fig. XX). The relief is the typically hillocky with the absolute heights up to 228 m above see level (asl).

There year-round meteorological observations were started in 1961 in Novolazarevskay site (WMO index is 89512), and then Maitri site (WMO index is 89514) was opened in 1989 (Turner and Pendlebury, 2004).

Fig. 1. Study region and the lakes studied (dark blue): based on the map of the Schirmacher oasis (Map of scale 1:25000, 1972).

2.1 Climate and weather in summer 2017–2018

There are two meteorological sites operating in the Schirmacher oasis since early 1980s namely Novolazarevskaya (Novo) and Maitri. Novo operates since August 1980, and these observations are representative for uphills areas of the oasis (Report of 31 SAE, 1986). Maitri site supports the observations representative for downhills, and it is located 5.0–5.5 km from Novo site. Both stations are included in the long term monitoring, and their measurements are done according to standards by the Word Meteorological Organization (Turner and Pendlebury 2004).

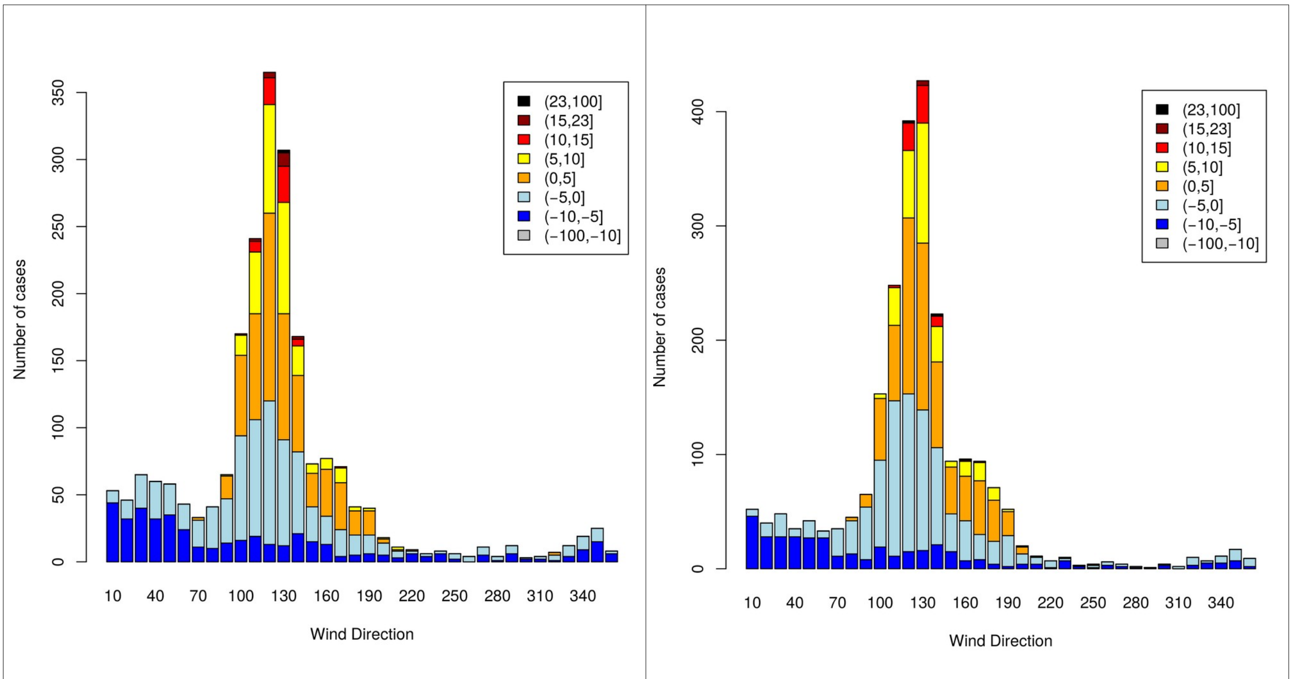
The local climate is featured by low humidity, cold temperature and persistent (katabatic) winds blowing most of the year. The easterly-southeasterly wind blows from the continental ice sheet, and it brings coldness to the oasis (Richter and Bormann, 1995). Maximal wind speed may reach up to 38 ms^{-1} in winter, however the winds become less strong in summer with the average wind speed of 8.0 ms^{-1} (Delevendra, 2019). In winter (June–August), the air temperature ranges from −4.5 to −12.9 °C (Govil et. al., 2016 after Lal, 2006). In summer (December–February), the average air temperature varies from –0.1 to to −3.0 °C. Table XX shows weather conditions during the field experiment and 20 year climatology of the Schimacher oasis according to observations at Novolazarevskaya (Novo) meteorological site (70°46′36.34″S, 11°49′20.48″ E). The climatology was extracted from the http://www.nerc-bas.ac.uk/icd/gjma/novol.temps.html.

Table 1. Climate and weather during the field experiment 2017–2018 according to Novo site.

Parameter	Period	December	January	February
Air temperature, °C	climatology 2017 2018	 -5.7/-0.1/5.2 –	 – -11.0/-1.3/4.5	 – -10.4/-3.0/3.4
Relative Humidity,%	climatology 2017 2018	 15/50/92 –	 – 22/57/94	 – 23/49/93
Atmospheric pressure, Pa	climatology 2017 2018	 960.3/970.2/986.2 –	 – 954.5/969.9/987.0	 – 954.7/966.6/977.3
Wind speed, ms^{-1}	climatology 2017 2018	 7.0 –	 – 6.2	 – 9.4
Soil Temperature, ºC	climatology 2017 2018	 -1.0 /5.0 /14.0 –	 – -8.0 /3.0 /13.0	 – -8.0/ 0.0/ 8.0
Incoming solar radiation, W m^{-2}	climatology 2017 2018	 917.61 –	 – 781.86	 – 468.15

*Min / Mean / Max

Wind direction and frequency of wind speed anomalies for eight ranges are given in the Fig. XX. It presents distributions calculated based on the observations collected during the period of 1999–2017 (see the Supplement).



a) December	b) January

Fig. XX. Wind direction and frequency of wind speed anomalies (according to Novo meteo site).

PD: some sentences on the Maitri site, and measurements in season 2017-2018. What was the weather conditions during this summer?

In this study, the series of the daily mean values of the air temperature, the winds speed and direction, the relative humidity were calculated from values measured at Maitri meteorological site for two periods: December, 2017 – February, 2018 and December, 2019 – February, 2020. In the first period, the daily *air temperatures* range from XX to XX ºC (Fig. XX a). Wind characteristic (speed and direction) in the season 2017 – 2018 was closed to the multi-years climatology (Fig. XX b), the wind speed ranges from XX to XX ms^{-1}., with the s average of over 7.4 ms^{-1}. There are several wind storms lasted up to a couple of days are observed in 2–3 of January, 2018, 3–4 February, 2018. During these storms,the measured wind speed were reached up to 30 m s^{-1}.

2.2 Lakes

In this region, there are more than 300 lakes documented in the SCAR Antarctic Digital Database (2008). Most of them are small ponds occupying the local depressions, and they do not connected to the ice sheet (the land locked type lake). Therefore, the seasonal snow cover melting is only source of water to these lakes. These small and shallow lakes are fully free ice during the summer seasons (Loppman and Klokov, 1988). There also a number of big lakes, which are connected with the ice-sheet (the epi- glacial or pro-glacial type lake). The epiglacial lakes have various portion of the glaciated area in their catchments, and it affects much to their thermal regime, water balance and freeze-up/break-up regime in summer (Fig. XX). The epiglacial type lakes with high portion of the glaciated area in their catchments can be fully ice covered during the summer seasons. The epiglacial lakes with low portion of the glaciated area are usually free of ice in January–February (Asthana et al., 2019). The thermal regime of the local lakes highly depends on weather conditions and regime of incoming solar radiation (Richter et al., 1995).

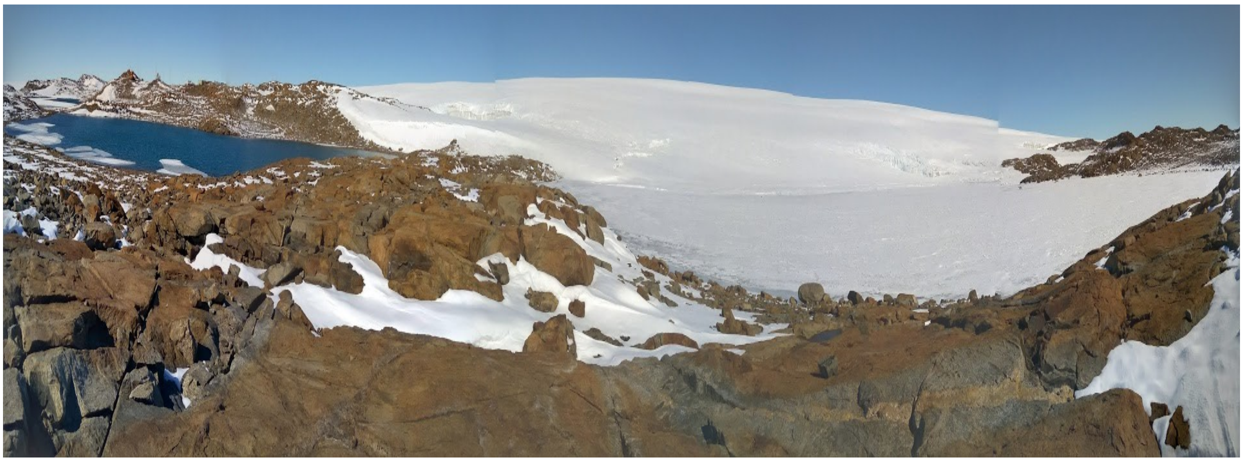


Fig. XX. Two epiglacial lakes with various portion of the glaciated area in their catchments: Lake Pomornik (left) with less then 30 % of glaciated area; and Lake Smirnova (right) with more than 60% of glaciated area (photo E. Shevnina, January, 2018).

In this study, we focused on the estimation of the evaporation rate over ice free surface of the Lake Zub/Priyadarshini (Table XX). This lake is of the epiglacial type, and its catchment area is glaciated for less then 30 %. The lake surface is free of ice during almost two summer months from mid-December to mid-February, and the surface water temperature rise up to 10-12 ºC (Shevnina. 2020; Khare et al., 2008; Sinha and Chatterjee, 2000). The lake supports the water supply of the Maitri scientific base year-roundly, and the maximum water consumption is corresponded to a summer season, when the population of the station increases twice. This up-taking of water is not significant term of the lake water budget (Dhote et al., 2021).

Table XX. The volume (V, 10^3 m^3), surface area (A, 10^3 m^2), depth (d_{mean} and d_{max}, m), water level height/level (h, m asl) of Lake Zub/Priyadarshini.

Source	V, 10^3 m^3	A, 10^3 m^2	d_{mean}, m	d_{max}, m
Khare et al., 2008	99.9	33.9	2.90	5.90
Dhote et al., 2020	1032500 m3	0.35 km2	2.95	–

3 Data and methods

3.1 Data

The evaporation was estimated from the special observations collected during the field experiment in January–February, 2018. In this experiment, the flux tower was deployed on the coast of the Lake Zub/Priyadarshini to collect the high frequency data on the atmospheric fluxes and water vapor concentration. Also, the temperature sensors were deployed to measure the water surface temperature in the lake (Fig. XXa). The experimental data were used to estimated the daily evaporation rate with the direct eddy covariance method and indirect methods namely the bulk-aerodynamic method, the energy budget method and the Dalton type semi-empirical equations. In additional, we used the standard meteorological observations collected by the Maitri site (**WMO Index, lat lon coordinates**) to estimate the evaporation after the semi-empirical equations. The ERA5 reanalyse was used in the estimations of the evaporation with the energy budget method.

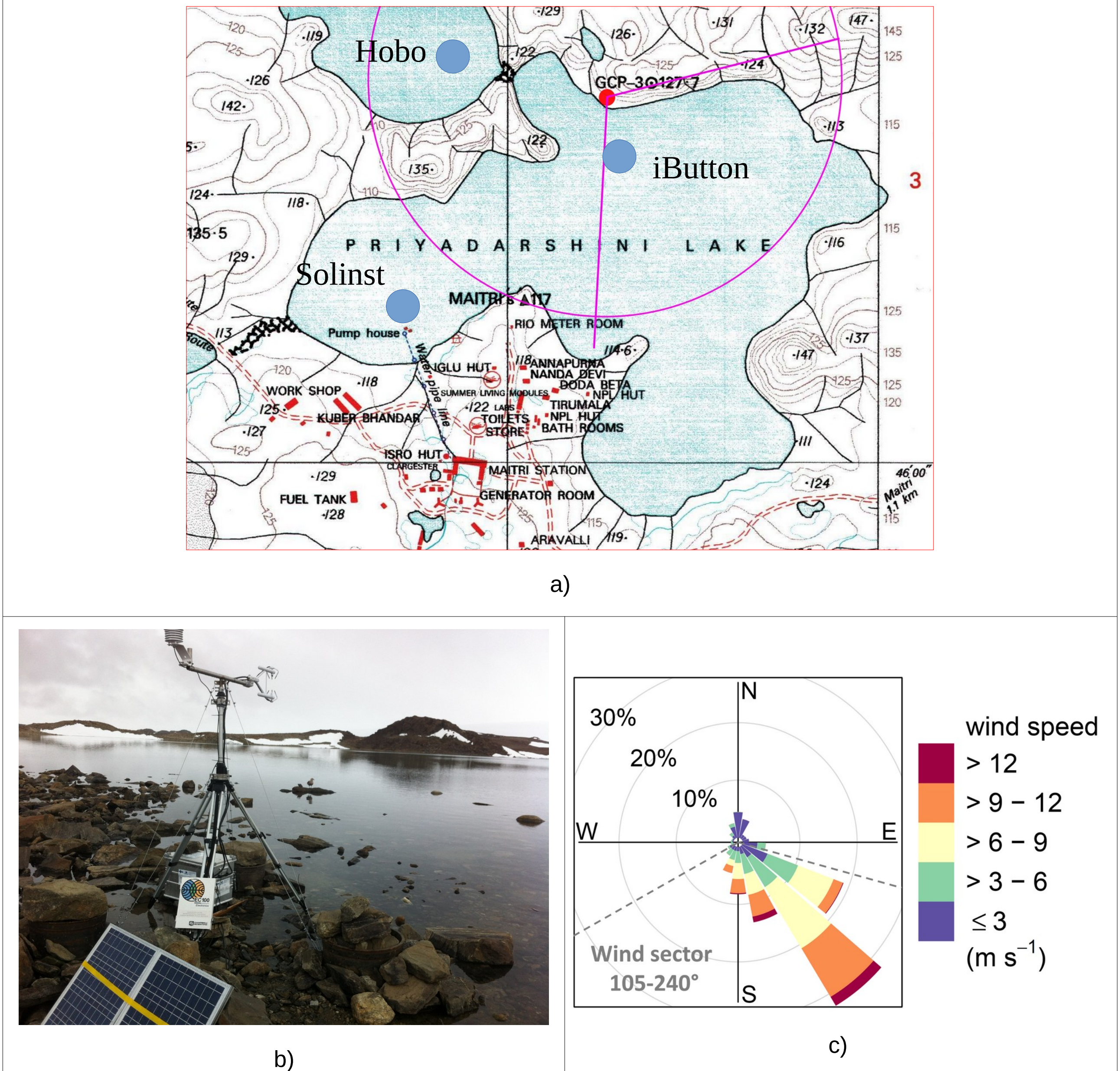


Fig. XX. Lake Zub/Priyadarshini: (a) – the temporal observational network deployed during the field experiment; (b) – the flux tower deployed on the coast of the lake (06.01.2018, photo by E. Shevnina); (c) – the wind speed and direction measured by the flux tower within the footprint wind sector (105˚–240˚): the length of the wedges indicates the frequency of counts by WD (%), the colors the respective WS per WD bin (equals to 20°).

The special observations were done in the field experiment during the austral summer 2017–2018. In this experiment, the water temperature was measured with three different instruments namely Hobo and Solinst water level/temperature sensors and the iButton temperature sensor (**Use guide 1,2,3**). The temperature sensors were deployed on the depth of 0.20 m. The Solinst and Hobo sensors were also measured the barometric pressure allowing to evaluate the water level/stage in the lake, however we did not used these data in this study. The measurements of the lake water temperature cover various observational periods, and data have been collected with different frequency (Table XX). The longest observational pe riod lasts from 01.01.2018 to 15.12.2018, and the data are collected by the Solinst temperature sensor, which recorded with the data every 30 minute (Dhote et al., 2020). The temperature sensors Hobo and iButton were recorded the surface water temperature every 10 minute during different periods (Table XX). The daily series of the surface water temperature was evaluated from these records.

Table XX. The hydrological and meteorological variables collected during the field experiment on the Lake Zub/Priyadarshini.

Instrument	Measured variables	Period	Method
Irgason	Air temperature, ºC; barometric pressure, Pa; H_2O concentration, g/m^3; 3D wind speed, ms^{-1}	01.01.2018 – 07.02.2018	Eddy covariance; bulk-aerodynamic
Hobo Solists iButton	Water temperature, ºC – –	30.12.2017 – 09.02.2018 01.01.2018 – 15.12.2018 27.01.2018 – 09.02.2018	Bulk-aerodynamic; semi-empirical equations
Records of the Maitri meteorological site	Air temperature, ºC; wind speed, ms^{-1}; relative humidity, %	01.12.2017 – 28.02.2018	Semi-empirical equations

To evaluate the evaporation rate with the direct eddy covariance method, we used the data collected in the field experiment lasted from 1 January to 7 February. In the experiment, the air temperature, barometric pressure, wind speed/direction and water vapor concentration were measured by the flux tower placed on 5–6 m to the lake coastline. The flux tower was fixed with 6 metal guidelines angled 120° to each others (Fig. XXb), and then it was equipped with the Irgason by Campbell Scientific (User guide, 2016). The Irgason was deployed on the boom in 2 m height, and the gas analyzer was directed according to the prevailing wind directions (Fig. XX).

In the eddy covariance method, a concept of “a footprint” is important to evaluate correctly the fluxes. The footprint is defined by a sector of wind direction covering source area, and depend on the height of the sensors (Burba, 2013). In our experiment, we have deployed the Irgason with accounting to prevailing wind directions (south, south-east). It allows to collect the majority of measurement from the source area covers the lake surface (Fig. XXc). The special observations cover a period of 38 days. The raw data consist of the values measured on a frequency 10 Hz. These raw data was used to calculate 30 minute series of the fluxes (the momentum flux, the sensible heat flux, the latent heat flux), the water vapor concentration, the specific humidity and turbulence parameters. The filtered series of these variables were further used to estimate the evaporation rate with the eddy covariance method. We also used the measurements collected in the field experiment 2018 to estimate the evaporation with the bulk-aerodynamic method and semi-empirical equations. The records of the Maitri meteorological site were used to evaluate the evaporation rate after the semi-empirical equations.

We used the ERA5 reanalyses (XX) to evaluate the evaporation rate with the energy budget method. The ERA5 data on the near surface energy budget were extracted at the model grid point nearest to the Novo site (70° 45´ 00´´S; 11° 45´ 00´´E), which is located in the ice-free area of the Schirmacher oasis (Fig. XX). Since, the native ERA5 model data has not regular lat-lon grid, and the zonal resolution of the native model grid is reduced towards poles as the distance between longitudes degreases towards poles, it is difficult to evaluate the area which was covered by the model gird cell. Generally, we would expect that the air temperature and dew point temperature in the ERA5 are probably comparable with those in the Novo site, at least in windy conditions.

3.2 Methods

To evaluate the evaporation rate with the direct *eddy covariance method (**MP**)*, we used the data collected by the 3D anemometer and gas analyser (Irgason by Campbell Scientific), and the raw data consist of the values measured with frequency of 10 Hz. To calculate the series of 30-minute values, the raw data were filtered in three steps: in the first step, the time intervals covered by less than 50 % of total measurements were excluded; on the second step, we excluded all data with non zero values in the quality flag, and the data with the gas signal strength was less then 0.7. On the third step, the raw data were processed to remove the spikes after the method given by Vickers and Mahrt (1997). This procedure was repeated up to 20 times, or until no more spikes are found. Potes et al. (2017) provide the detailed description of the post-processing procedure applied in this study. Then, we also filtered the data withing the footprint of the lake surface, which is covered the winds with the direction ranging from 105 to 240º (Fig. XX c). In our experiment, the Irgason was deployed with the accounting to prevailing wind directions (Fig. XX), therefore, only 18 % of the total measurements were excluded from further consideration because they represented the footprint outside the lake surface. Finally, the daily evaporation over the lake surface was estimated as the sum of 30-minute values in each day of the experimental period. We also calculated the daily series of wind speed (*W*, m s^{-1}) and air temperature (T_{200}, ºC), and then used them in the evaluations after the Dalton type semi-empirical equations.

*The bulk aerodinamic method **(TV)**, the e*vaporation (kg m^{-2} s^{-1}) is defined as the vertical surface flux of water vapor due to atmospheric turbulent transport. It is calculated from the difference in specific humidity between the surface, and the air, as well as the factors that affect the intensity of the turbulent exchange: wind speed, surface roughness, and thermal stratification (Boisvert et al., 2020;). In our study, the turbulent fluxes of latent and sensible heat were calculated using the bulk-aerodynamic method, where the turbulent transfer coefficients for heat and moisture depended on the stratification in the atmospheric surface layer, and the aerodynamic roughness length depended on the wind speed. The calculations followed Launiainen and Vihma (1990), except that the neutral transfer coefficients for heat and moisture were set according to observations from a boreal lake (Heikinheimo et al., 1999) to better take into account the different regime of turbulent mixing over a small lake compared to the sea (Sahlee et al., 2014).

The evaporation rate was calculated with the formula:

where, the evaporation rate is expressed in mm day^{-1}; ...

In the *semi-empirical equations (**ES, PD**)*, the evaporation rate (mm day^{-1}) is calculated from a wind function and the gradient of the temperature of water and air:

$$E = f(\bar{w}_{200})(e_s - e_{200}) \quad ,$$

where, E is daily evaporation; e_s is the water vapor saturation pressure; e_{200} is the water vapor pressure at 2 meter height; $f(\bar{w}_{200})$ is the wind function evaluated from observations (or empirically). There are many empirical approximations for the regional coefficients in the wind function (XXX). In this study, we applied three semi-empirical equations to calculate the daily evaporation rate:

$$E = 0.26(1 + 0.54 w_{200})(e_s - e_{200}) \quad , \qquad \text{(Penman, 1948)}$$

$$E = 0.26(1 + 0.86 w_{200})(e_s - e_{200}) \quad , \qquad \text{(Doorenbos and Pruitt, 1975)}$$

$$E = 0.14(1 + 0.72 w_{200})(e_s - e_{200}) \quad ,$$ (Odrova, 1979)

where, water vapor saturation pressure is given in millibars, and evaporation rate is expressed in mm day^{-1}. To calculate water vapor saturation pressure, we used the Tetens's formula:

$$e = b_1 exp\left[\frac{b_2 t}{(t + 273.15 - b_3)}\right]$$

where, *t* is the air temperature measured at 2.0 m height (e_{200}) or the surface water temperature measured at the depth of 0.2 m (e_s); b_1, b_2 and b_3 are empirical constants for the open surface of water, b_1 =611.3, b_2 = 17.2694 and b_3 = 35.86 (Stull, 2017). In this study, we also calculated the evaporation rate from the meteorological observations collected at the Maitri site.

In *the energy budget method (**TN**)*, the evaporation rate was calculated as:

We evaluated the evaporation over the ice free surface of the Lake Zub/Priyadarshini with various methods needed to compare to a reference method. The eddy covariance method gives the best accuracy while estimating the evaporation rate (Tanny et al., (2011), therefore it was considered as the reference in this study. To estimate the efficiency of the indirect methods we used the Pearson correlation coefficient (XXX), the Nash-Sutcliffe efficiency index (Nash and Sutcliffe, 1970) and the s/σ criteria (Popov, 1979).

The Pearson correlation coefficient reads:

XXX

The Nash-Sutcliffe index reads:

$$NSE = 1 - \frac{\sum_{i=1}^{n}(E_m^i - E_{EC}^i)^2}{\sum_{i=1}^{n}(E_{EC}^i - \bar{E}_{EC})^2}$$

where, E_m is the modeled evaporation (the indirect methods); and E_{EC} is the evaporation (the eddy covariance method)

the s/σ criteria reads:

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

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}(E_{EC}^i - E_m^i)^2}{(n-m)}} \quad ????$$

where, n is the length of series, and m is a number of the empirical coefficients in the wind function.

4 Results

In the field experiment, the flux tower was placed on the coast of the Lake Priyadarshiny for the period of 01.01.2018 to 07.02.2018 (38 days). During the field experiment, the atmospheric conditions over the lake surface were characterized by unstable stratification, with the lake surface temperature typically exceeding the 2-m air temperature by 4-5 ºC (Figure XXa). The diurnal temperature cycle was evident, and regular particularly for the lake surface temperature. The time series of the 2-m wind speed over the lake shore demonstrates combined effects of synoptic-scale variations and a diurnal cycle.

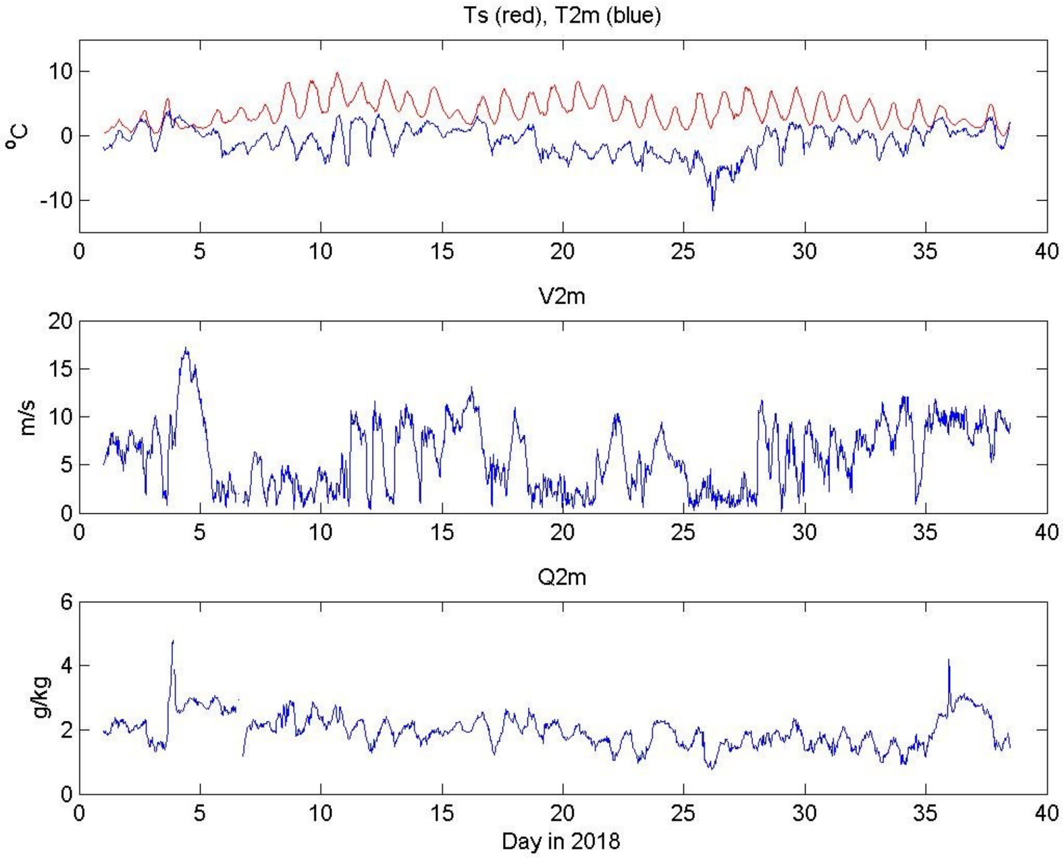


Figure XX. Time series on the lake surface temperature and the 2-m air temperature, wind speed and specific humidity. (more variables)

One paragraph on the each sub-figure in the graph.

*In the eddy covariance (EC) method (**MP**)*, the daily evaporation rate was calculated as the sum for the series of 30 min evaporation rates estimated from the fluxes measured within each day in the period of 38 day in the experiment in the Lake Zub/Priyadarshini. Table XX shows the summary statistic for the measurement collected by the flux tower during two experiments on the lakes. In season 2017–2018, the maximal and mean of the wind speed were 17.5 m s^{-1} 5.9 m s^{-1}, respectively. Of over 72 % of the measurements were collected within the footprint covering the surface of the Lake Zub/Priyadarshini (red dots in the Fig. XX).

Table XX. The summary statistic for 30 minute series of the variables after the filtering.

Variable name	Mininum / Mean / Maximum
Wind speed, ms^{-1}	0.2 / 5.9 / 17.3
Wind direction, degree	/ 150 /

H2O concentration, (g m^{-3})	1.02 / 2.53 / 6.07
Pressure, kP	955.2 / 971.2 / 988.4
Air temperature, C	–11.6 / –0.8 / 3.9
Sensible heat flux, W m^{-2}	–26.1 / 51.6 / 155.8
Latent heat flux, W m^{-2}	–17.9 / 90.6 / 216.1
Evaporation, L m^{-2}	–0.012 / 0.064 / 0.155

Fig. XX shows the series of the sensible heat and latent heat fluxes calculated after the EC method, where the red dots indicate the measurements collected outside the footprint of the lake surface. Further, these “missing” data were replaced by the mean of 30-minute series of the evaporation rate.

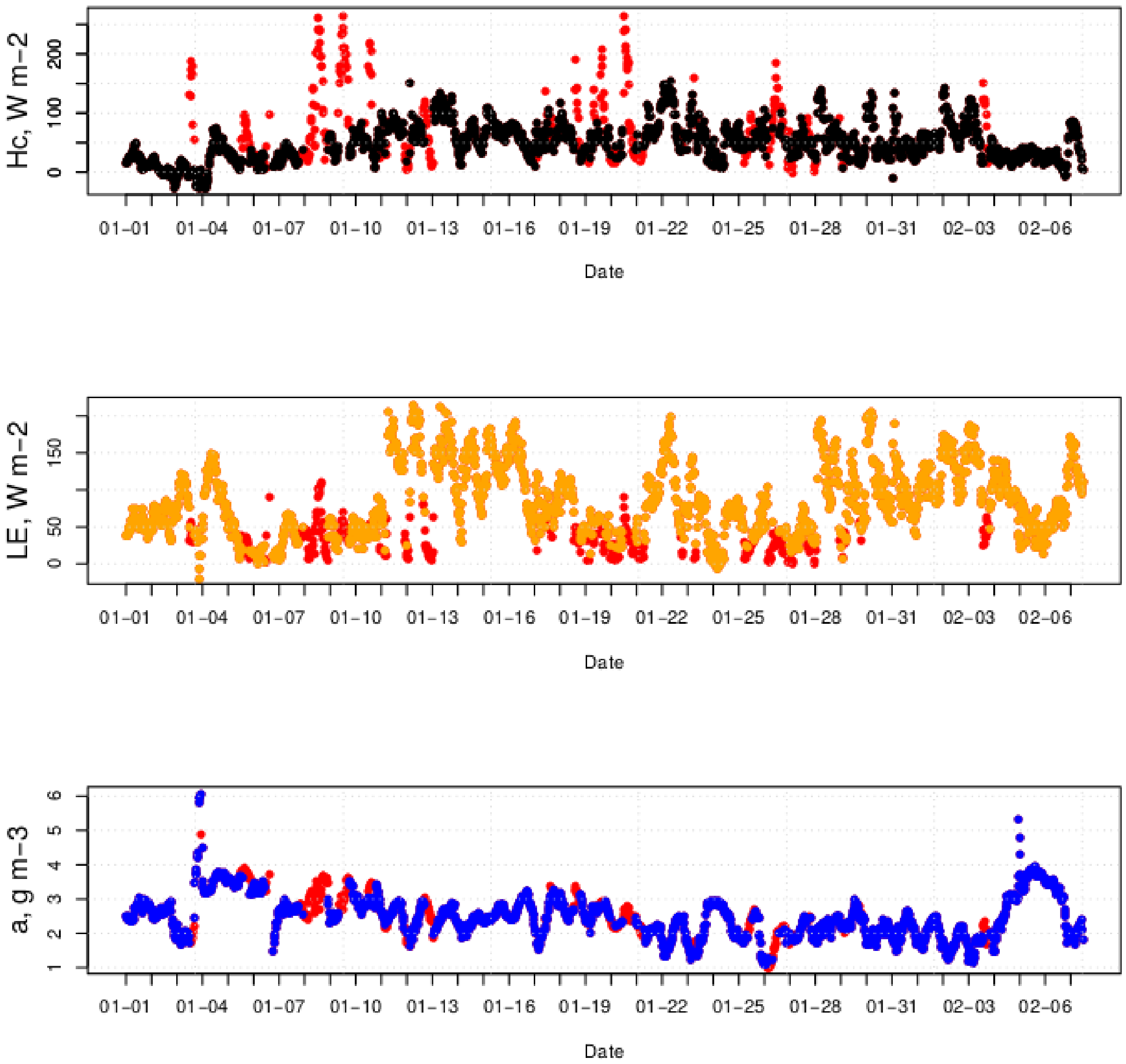


Fig. XX. 30 minute series of the sensible heat flux humidity (H, W m^{-2}), the latent heat flux (LE, W m^{-2}), and H2O concentration (*a*, g m^{-3}) measured over the open surface of Lake Zub/Priyadarshini.

Our results after the EC method shows that the daily evaporation rate vary from 1.5 to 5.0 mm day^{-1} with the mean value equals to 3.0 mm day^{-1}. Over the period of 38 days, it results to 114 mm of water evaporated over the lake surface. These daily series of the evaporation rate after the EC method were further considered as the reference values to compare to the results of the indirect methods.

T*he bulk-aerodynamic method (**TV**):* The sensible and laten fluxes calculated with the bulk-aerodynamic method were compared against those estimated after the eddy-covariance measurements (Figure XX). The latent heat fluxes showed a very high correlation coefficient of 0.93, but the eddy-covariance measurements showed a larger mean value (80 W m^{-2}) than the bulk method (59 W m^{-2}). The results for the sensible heat flux were analogous with larger values according to the eddy covariance measurements (mean value 58 W m^{-2}) than the bulk method (40 W m^{-2}). The correlation was weaker (r = 0.47) related to a more frequent occurrence of high peak values in the eddy covariance data (Figure XX).

The Bowen ratio typically ranged from 0 to 1.5, with negative values only in a few days when downward sensible heat flux occurred simultaneously with evaporation.

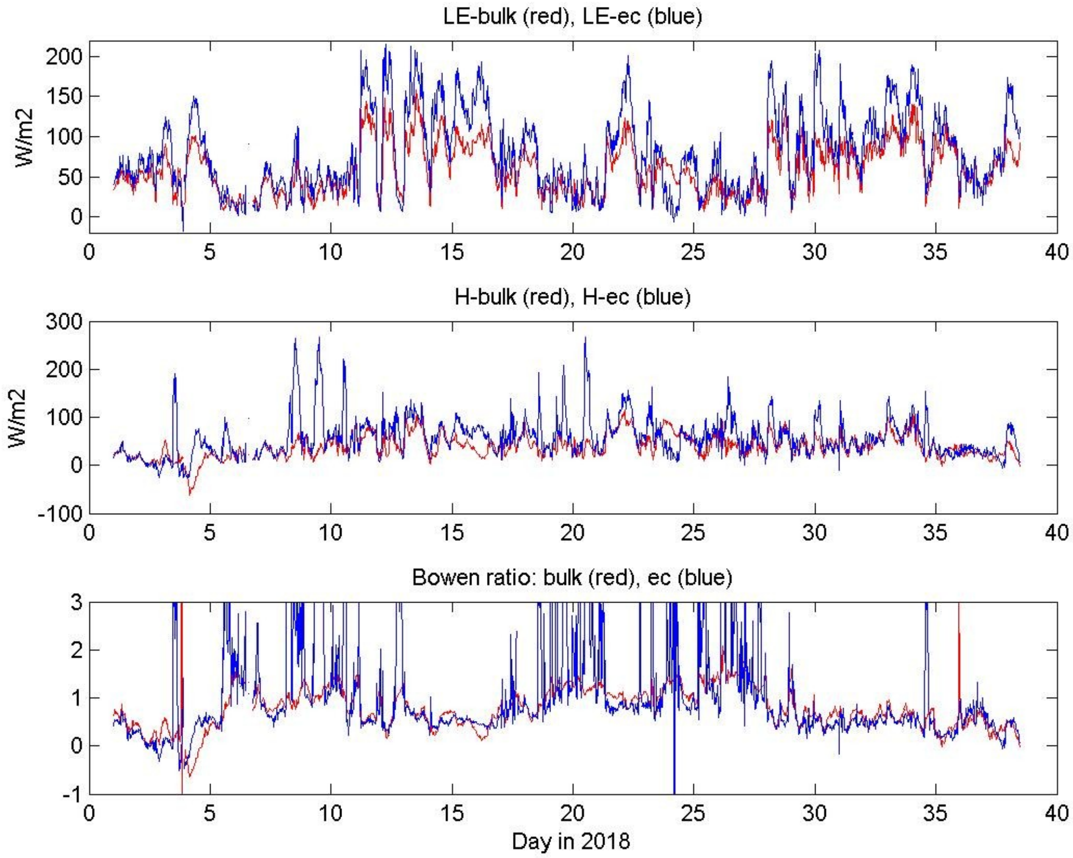


Figure XX. Time series of the latent heat flux, sensible heat flux, and the Bowen ratio.

Figure XX further illustrates the scatter between the bulk and eddy-covariance methods. Some cases deserve more attention. Both on the basis of the bulk and eddy-covariance methods, variations in the latent heat flux were mostly controlled by the wind speed (Table XX).

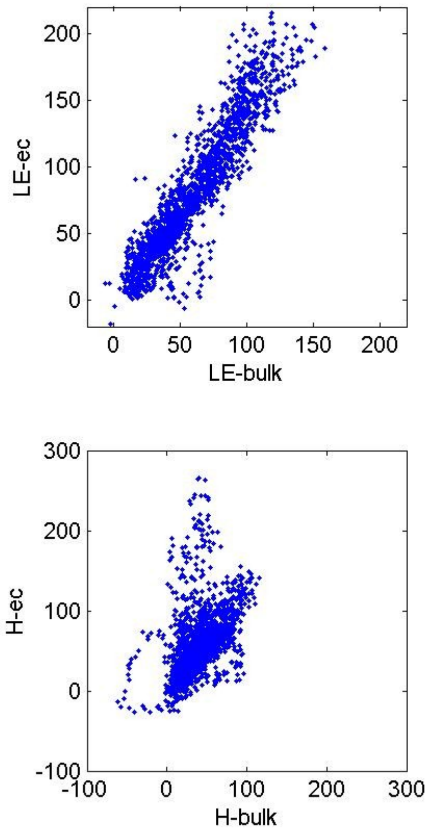


Figure XX. Scatter plots of the turbulent fluxes of latent and sensible heat based on the eddy-covariance and bulk methods.

Table XX. Correlation coefficient between the turbulent fluxes of latent and sensible heat and the boundary conditions that theoretically affect them.

Variable	LE-bulk	LE-ec	H-bulk	H-ec
V2m	0.80	0.73	0.10 (0.23 for |H|)	-0.01 (0.00 for |H|
Q2m	-0.20	-0.29		
T2m			-0.28	-0.11
Ts	-0.02	-0.09	0.33	0.35
Ts-T2m			0.47	0.34

The air specific humidity and surface temperature (the latter controlling the surface saturation specific humidity) only showed very low correlations with the latent heat flux. Surprisingly, the wind speed correlated neither with the sensible heat flux nor with its absolute value. This seems to result from the fact that even cases with a strong wind were often associated with very low sensible heat flux but a larger latent heat flux (Figure XX). This may suggests a role of katabatic winds, which advect dry but adiabatically warmed air to over the lake. In the same event, the shear-driven mixing may be sufficient to eliminate the temperature differences between the lake surface and air, but not the specific humidity differences, which are large due to the initially dry air mass. The variations in sensible heat flux are related to variations in the lake surface temperature and its difference from the 2-m air temperature, but the correlations are weak (Table XX).

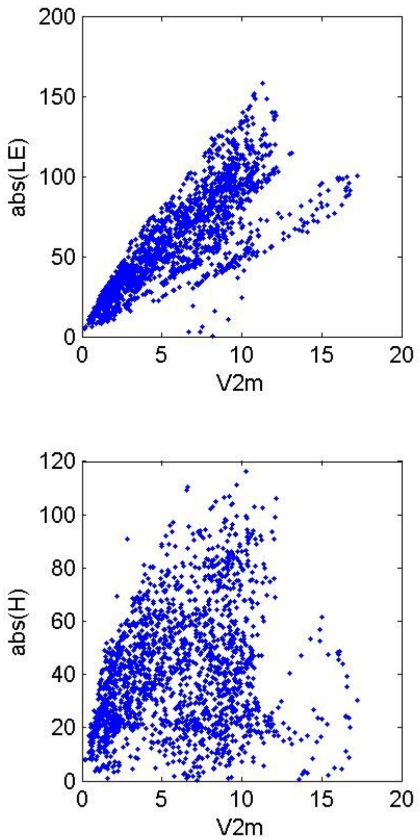


Figure XX. Scatter plots of the turbulent fluxes of latent and sensible heat (based on the bulk method) and the 2-m wind speed.

The daily evaporation rate calculated after the bulk-aerodynamic method vary from **XX** mm day^{-1} to **XX** mm day^{-1}, and it takes of over **XX** mm day^{-1} in the mean value.

*The semi-empirical equations (**ES, PD**):* In this study, we applied the semi-empirical equations by Penman (1948) and by Doorenbos and Pruitt (1975) to evaluate the daily evaporation rate from the meteorological variables measured by the Irgason (Table XX). We also used the semi-empirical equation after Odrova (1979) from the meteorological records collected by the Maitri site (Table XX). We used the air temperature, relative humidity and wind speed observed during the period the field experiment to calculate the daily evaporation rate.

XXX

The energy budget suggests of over XX mm day-1 for the daily evaporation rate during the period of the experiment. The energy budget method from the ERA5 data suggests the estimations of evaporation during summer (DJF) 2017-2018 was 0.61mm day^{-1}, and it is only one fifth of the evaporation estimated with the direct method.

XXX

Table XX shows the mean daily evaporation rate calculated with the direct and indirect methods.

Table XX. The statistic of the measured (E_{EC}, mm) and modeled (E_{MM}, mm) daily evaporation rates for the experiment on the Lake Zub/Priyadarshini.

E_{MM} (Model / Dataset)	Min/Max	Average ± SD	*E*

			(mm period^{-1})
ERA5	0.0 / 2.0	0.5 ± 0.4	20
Bulk-aerodynamic method			
Penman, 1948 / Irgason	0.7 / 3.6	2.4 ± 0.7	90
Doorenbos and Pruitt, 1975 / Irgason	1.1 / 5.3	3.4 ± 1.1	129
Odrova 1979 / Irgason	0.5 / 2.5	1.6 ± 0.5	60
Odrova 1979 / Maitri	0.4 / 5.1	2.0 ± 1.1	77
EC method	1.5 / 5.0	3.0 ± 1.1	114

Among the indirect methods, the equation after Doorenbos and Pruitt (1975) give the closest fit to the evaporation rate evaluated from the direct methods. All equations overestimated the daily evaporation rate, and the sum over whole 38 day period are also overestimated from XX % (case: Penman, 1948) to XX % (in the case of the equation by Doorenbos and Pruitt, 1975). XXX

Figure XX show the series of the daily evaporation rate (mm day-1) estimated with the direct and indirect methods.

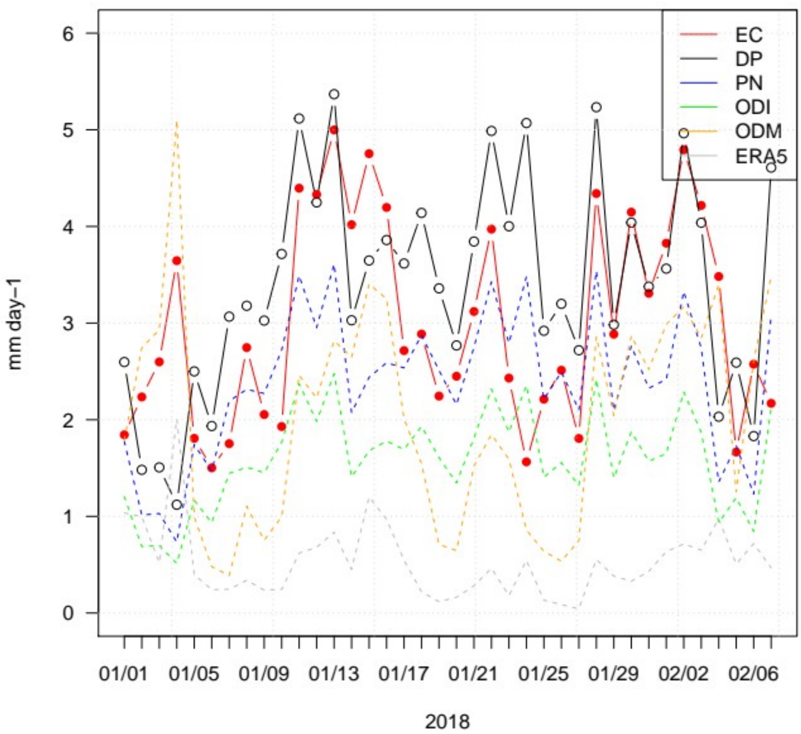


Fig. XX. The daily evaporation rate (mm day-1) estimated with various methods:

The energy budget method from the ERA5 data suggests the evaporation during summer (DJF) 2017-2018 was 0.61mm day^{-1}, and it is only one fifth of the evaporation estimated with the EC method. Since the ERA5 has horizontal resolution, approximately 30 km, therefore it cannot resolve accurately evaporation over fine structures of surface. The area of Schirmacher Oasis, approximately a couple of tens square kilometres, are practically too small to be well presented in ERA5, grid cell area is approximately 900 km^2. The surface on Schirmacher Oasis during summer time is mostly snow free and thus has low albedo, which results a large gain of energy due to absorbed solar radiation. Instead, the closest grid cell in ERA5 has a large surface albedo, and it results that always less than 17 % of the daily incoming solar radiation is absorbed to surface, which may be representative for surrounding ice and snow covered area but not for Schirmacher Oasis area. In the ERA5, the evaporation rate is below 1.5 mm day^{-1} almost every day during summer 2017-2018, except one day.

Table XX shows the efficiency of the indirect methods applied in the estimations of the daily evaporation rate. The efficiency is evaluated with the Pearson correlation coefficient (*R*), the Nash-Sutcliffe index (*NSI*) and s/σ criteria (*SSC*).

Table XX.

E (mm day^{-1})	*R*	*NSI*	*SSC*
ERA5	0.43		2.54
Bulk-aerodynamic method			
Penman, 1948	0.42		1.12
Doorenbos and Pruitt, 1975	0.48		1.11
Odrova 1979	0.46		1.62
Odrova 1979 (+Maitri)	0.68		1.26
EC method	1		–

5 Discussions

The evaporation rate is directly measured with evaporimeters (WMO, 2008). Indirect methods to estimate the evaporation include bulk transfer equations, energy balance, water balance, empirical formulae and combination techniques (Finch and Hall, 2001; Chebotarev, 1986; Brutsaert, 1985). Abtew and Melesse, (2013) suggest that choose of the calculation method is done by fitting “ an accuracy needed, available input data, and cost of data generation” in practice. In the remote Antarctic continent, the measurements by the evaporimeters or with the eddy covariance systems are difficult to carry out, thus the evaporation/sublimation rate are estimated only indirectly from the meteorological observations provided by automatic weather stations.

Sene et al., 1991:

Borghini et al. 2013

Shevnina and Kourzeneva (2017) use the empirical equation after (Odrova, 1979) and energy budget methods (after Mironov, 2008) to evaluate daily evaporation rate for lakes located in the King George Island (sub- Antarctica) and the Larsemann Hills oasis (East Antarctica).

Franz et al., 2018:

Faucher et al., 2020:

Rodrigues et al. 2020:

Boisvert et al. 2020:

Naakka et al., 2021:

It seems that there are more than 65,000 supraglacial lakes in the area. The total surface of these lakes was 1385 km2 in January 2017 (summer weather conditions were similar to climatology mean). The average daily evaporation from the lake surface is about 2-3 mm day-1.

Would these lakes become visible in ERA5? How significant may be underestimations of the daily evaporation over the East Antarctic coast if the lakes are ignored?

//In ERA5, each grid cell has been divided to tiles regarding surface types. Surface types includes, several land surface types, lakes or coastal water, and 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. Relative area of each surface type on a grid cell importantly affects its contribution to grid cell mean surface fluxes, which are available in ERA5 data, but surface fluxes separately for each tile are not available. Therefore, the contribution of evaporation from lakes in grid cell mean evaporation would be small, if their relative area is small, even though they were correctly modelled in ERA5. In our recent study, mean evaporation on East Antarctic Slopes was on average 0.24 mm/day, which is thus approximately 10% compared with evaporation from supraglacial lakes. Total surface area of those lakes compared with the whole coastal area of East Antarctica seems to be relatively small, and therefore it probably would not cause notable underestimation of evaporation, even though the lakes ignored, and even though the evaporation from the lakes was ten time larger than mean evaporation. However, I do not know how well supraglacial lakes are modelled in ERA5. Even though supraglacial lakes significantly increased evaporation in local scale, it would probably not have a large effect on the grid cell scale (approx.. 900 km2) of ERA5.

6 Conclusions

The cumulative evaporation over the Lake Zub/Priyadarshini was 114 mm in January–February, 2018. The daily evaporation rate exhibit the peaks on evaporation up to 7.4 mm per day, with daily mean and max values of over 2.9 and 5.9 mm per day for the whole measured period.

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Supplements.

Data availability. Shevnina, E. (2019a). 3D wind speed and CO2/H20 concentration measurements collected during austral summer 2017/2018 over an ice free surface of a shallow lake located in the Schirmacher oasis, East Antarctica. [Data set]. Zenodo. http://doi.org/10.5281/zenodo.3469570

Shevnina E., (2019b). Water temperature measurements collected during austral summer 2017/2018 on lakes located in the Schirmacher oasis, East Antarctica. [Data set]. Zenodo. http://doi.org/10.5281/zenodo.3467126

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References

Abtew W., Melesse A., 2013: Evaporation and Evapotranspiration Estimation Methods. In: Evaporation and Evapotranspiration. Springer, Dordrecht, doi: 10.1007/978-94-007-4737-1_6

Andersen, D.T., McKay, C.P. and Lagun , V. 2015:. Climate conditions at perennially ice-covered Lake Untersee, East Antarctica. Journal of Applied Meteorology and Climatology, 54, 1393–1412.

Asthana, R., Shrivastava, P.K., Srivastava, H.B., Swain, A.K., Beg, M.J., & Dharwadkar, A. (2019). Role of lithology, weathering and precipitation on water chemistry of lakes from Larsemann Hills and Schirmacher Oasis of East Antarctica, Adv Polar Sci, 2019, 30(1): 35-51, doi: 10.13679/j.advps.2019.1.00035

Aubinet M., Vesala, T., Papale, D. (Eds). 2012: Eddy Covariance: A Practical Guide to Measurement and Data Analysis, ISBN 978-94-007-2350-4e-ISBN, DOI: 10.1007/978-94-007-2351-1

Boisvert, L., Vihma, T., Shie, C.L., 2020: Evaporation from the Southern Ocean estimated on the basis of AIRS satellite data. Journal of Geophysical Research: Atmospheres, 125, e2019JD030845. https://doi.org/10.1029/2019JD030845

Boronina A.S., Popov S.V., and Pryakhina G.V.: Hydrological characteristics of lakes in the eastern part of the Broknes Peninsula, Larsemann Hills, East Antarctica, Led i Sneg, 59 (1), 39–48, doi: 10.15356/2076-6734-2019-1-39-48, 2019. [In Russian].

Bormann, P., Fritzsche, D., 1995. The Schirmacher Oasis, Queen Maud Land, East Antarctica, and Its Surroundings. Justus Perthes Verlag Gotha, Darmstadt, 448 pp.

Boisvert, L., Vihma, T., and Shie, C.-L., 2020: Evaporation from the Southern Ocean estimated on the basis of AIRS satellite data. *Journal of Geophysical Research: Atmospheres*, 125, e2019JD030845. https://doi.org/10.1029/2019JD030845

Braslavskiy, A. Calculation on evaporation rate from freshwater reservoirs located on flat areas. In book: Materials for a committee on study of methods to calculate an evaporation from water/land surfaces. GGI, Valday, 1966. (in Russian)

Borghini, F., Colacevich, A., Loiselle, S.A. *et al.* Short-term dynamics of physico-chemical and biological features in a shallow, evaporative antarctic lake. *Polar Biol* **36,** 1147–1160 (2013). https://doi.org/10.1007/s00300-013-1336-2

Brutsaert, W., 1982: Evaporation into the atmosphere - theory, history and applications, Dordrecht, Holland: D Reidel Publishing Company.

Brutsaert, W., 1985: Evaporation into the Atmosphere: theory, history and applications., Leningrad, Gidrometizdat, 1985, p. 53-60. (in Russian, English translation by Dubova A.)

Burba G. Eddy Covariance Method for Scientific, Industrial, Agricultural, and Regulatory Applications: A Field Book on Measuring Ecosystem Gas Exchange and Areal Emission Rates. LI-COR Biosciences, Lincoln, NE, USA. 2013, 331 p.

Burba, G., Y. Kurbatova, O. Kuricheva, V. Avilov, and V. Mamkin, 2016. Handbook for the Method of Turbulent Pulsations [Метод Турбулентных Пульсаций: Краткое Практическое Руководство]. LI-COR Biosciences, IPEE, Russian National Academy of Sciences, Moscow, Russia, 223 pp. ISBN: 978-0-692-57831-5

Delevendra S, Vimlesh P, Kamra A: Temperature-dependence of the positive intermediate ion concentrations at Maitri, Antarctica, Journal of Atmospheric and Solar-Terrestrial Physics. 2013; 104. DOI: 10.1016/j.jastp.2013.08.011

Doorenbos, J., Pruitt, W.O., 1975. Crop water requirements, FAO Irrigation and Drainage Paper No. 24 FAO Rome, 179pp.

Dhote et al., 2020:

Erkkilä , K-M , Ojala , A , Bastviken , D , Biermann , T , Heiskanen , J J , Lindroth , A , Peltola , O , Rantakari , M , Vesala , T & Mammarella , I 2018 , ' Methane and carbon dioxide fluxes over a lake : comparison between eddy covariance, floating chambers and boundary layer method ' , Biogeosciences , vol. 15 , no. 2 , pp. 429-445 . https://doi.org/10.5194/bg-15-429-2018

Faucher, B., Lacelle, D., Fisher, D., Andersen, D., & McKay, C. (2019). Energy and water mass balance of Lake Untersee and its perennial ice cover, East Antarctica. *Antarctic Science, 31*(5), 271-285. doi:10.1017/S0954102019000270

Finch, J. W. and Hall, R. L. 2001. Estimation of Open Water Evaporation: A Review of Methods, R&D Technical Report W6-043/TR. Environment Agency, Bristol, 155 p.

Finch, J. W. and Hall, R. L. 2005. Evaporation from Lakes. Encyclopedia of Hydrological Sciences, Part 4 Hydrometeorology Centre for Ecology and Hydrology, Wallingford. pp. 635–646

Franz, D., Mammarella, I., Boike, J., Kirillin, G., Vesala, T., Bornemann, N., et al. (2018). Lake-atmosphere heat flux dynamics of a thermokarst lake in arctic Siberia. *Journal of Geophysical Research: Atmospheres*, 123, 5222– 5239. https://doi.org/10.1029/2017JD027751

Girdiuk G V, Kirillova T V: Methodology to calculate the terms of radiation balance over the ocean. Meteor. Gidrol. 1974; 12:63–69. (in Russian)

Gorodetskaya, I. V., N. P. M. Van Lipzig, M. R. Van den Broeke, A. Mangold, W. Boot and C. H. Reijmer (2013), Meteorological regimes and accumulation patterns at Utsteinen, Dronning Maud Land, East Antarctica: Analysis of two contrasting years. J. Geophys. Res., 118, 1700-1715, doi:10.1002/jgrd.50177.

Govil, P., Mazumder A., Asthana R., Tiwari A., Mishra R., 2016. Holocene climate variability from the lake sediment core in Schirmacher Oasis region, East Antarctica: Multiproxy approach, Quaternary International (2016), http://dx.doi.org/10.1016/j.quaint.2016.09.032

Guidelines to calculate evaporation from water reservoirs. Leningrad, Gidrometizdat, 1969, 83 p. (in Russian)

Guidelines for hydrometeorological stations: Part 1. 1978. Gidrometizdat, Leningrad, 384 pp. (in Russian).

Gooseff, M. N., Lyons, W., McKnight, D. M., Vaughn, B. H., Fountain, A. G., & Dowling, C. (2006). A stable isotopic investigation of a polar desert hydrologic system, McMurdo dry valleys, Antarctica. Arctic, Antarctic, And Alpine Research, 38(1), 60-71.

Heikinheimo, M., M. Kangas, T. Tourula, A. Venäläinen, S. Tattari (1999). Momentum and heat fluxes over lakes Tämnaren and Råksjö determined by the bulk-aerodynamic and eddy-correlation methods, Agricultural and Forest Meteorology, 98–99, 521-534, https://doi.org/10.1016/S0168-1923(99)00121-5.

Henderson-Sellers, B. Calculating the surface energy balance for lake and reservoir modelling: A review Rev. Geophys., 1986, 24, 625-649, doi: 10.1029/RG024i003p00625.

Jammet, M., Crill, P., Dengel, S., and Friborg, T. (2015), Large methane emissions from a subarctic lake during spring thaw: Mechanisms and landscape significance, *J. Geophys. Res. Biogeosci.*, 120, 2289– 2305, doi:*10.1002/2015JG003137*.

Kaup, E., 2005: Development of anthropogenic eutrophication in lakes of the Schirmacher Oasis, Antarctica. Verh. Internat. Verein. Limnol. 29, 678-682.

Khare N., Chaturvedi S. K., Saraswat R., Srivastava R., Raina R., and Wanganeo A., 2008: Some morphometric characteristics of Priyadarshini water body at Schirmacher Oasis, Central Dronning Maud Land, Antarctica with special reference to its bathymetry. Indian Journal of Marine Sciences, 37(4), 435-438.

Konstantinov A.P., 1968: Evaporation in Nature, Hydrometeizdat, Leningrad, pp. 177 – 251.(in Russian).

Keijman, J.Q.:The estimation of the energy balance of a lake from simple weather data. Boundary-Layer Meteorol, 1974, 7: 399, doi: 10.1007/BF00240841.

Kljun, N., Calanca, P., Rotach, M.W. *et al.* A Simple Parameterisation for Flux Footprint Predictions. *Boundary-Layer Meteorology* 112, 503–523 (2004). https://doi.org/10.1023/B:BOUN.0000030653.71031.96

Larsen, A. S., O'Donnell, J. A., Schmidt, J. H., Kristenson, H. J., and Swanson, D. K. (2017), Physical and chemical characteristics of lakes across heterogeneous landscapes in arctic and subarctic Alaska, *J. Geophys. Res. Biogeosci.*, 122, 989– 1008, doi:*10.1002/2016JG003729*.

Linacre E. T.: Data-sparse estimation of lake evaporation, using a simplified Penman equation, Agricultural and Forest Meteorology, Volume 64, Issues 3–4, 1993, Pages 237-256, doi:10.1016/0168-1923(93)90031-C.

Launiainen J., and Vihma, T., 1990: Derivation of turbulent surface fluxes — An iterative flux-profile method allowing arbitrary observing heights, Environmental Software, 5,3, 113-114. https://doi.org/10.1016/0266-9838(90)90021-W

Loopman A., Kaup E., Klokov V., Simonov I., and Haendel D., 1988: The bathymetry of some lakes of the Antarctic oases Schirmacher and Untersee, in *Limnological Studies in Queen Maud Land* (East Antarctic), Ed. by J. Martin (Valgus, Tallinn), pp. 6–14.

Majidi, M.; Alizadeh, A.; Farid, A. & Vazifedoust, M. Estimating Evaporation from Lakes and Reservoirs under Limited Data Condition in a Semi-Arid Region Water Resour. Manage., 2015, 29:3711-3733, doi: 10.1007/s11269-015-1025-8.

Mammarella, I., Werle, P., Pihlatie, M., Eugster, W., Haapanala, S., Kiese, R., Markkanen, T., Rannik, Ü., and Vesala, T.: A case study of eddy covariance flux of N_2O measured within forest ecosystems: quality control and flux error analysis, Biogeosciences, 7, 427–440, https://doi.org/10.5194/bg-7-427-2010, 2010.

The Schirmacher oasis, the map of scale 1:25000, 1972

Messing I.: A simple practical evaporimeter: Comparison of Andersson evaporimeter with class a pan, piche atmometer, and penman evaporation, Arid Soil Research and Rehabilitation, 1998, 12:3, 275-290, doi: 10.1080/15324989809381516

Mironov, D., Golosov, S., Heise, E., Kourzeneva, E., Ritter, B., Scheider, N., and Terzhevik, A.: FLake – a lake model for environmental applications. In: Proceedings of the 9th Workshop on Physical Processes in Natural Waters (Folkard, A., and Jones, I. (eds.)). Lancaster University, Lancaster, 73 p., 2005.

Nash, J.E., Sutcliffe, J.V., 1970. River flow forecasting through conceptual models: Part I – A discussion of principles. J. Hydrol. 10, 282–290.

Odrova, T. Hydrophysic of water reservoirs. Leningrad, Gidrometizdat, 1979, 169-175. (In Russian)

Penman, H.L. *Natural evaporation from open water, bare soil and grass.* Proc. Roy. Soc. London A, 1948, 194:120-145. http://doi.org/10.1098/rspa.1948.0037

Phartiyal, B., Sharma, A. & Bera, S.K., 2011. Glacial lakes and geomorphological evolution of Schirmacher Oasis, East Antarctica during Quaternary. Quaternary International 23, 128–136, doi:10.1016/ j.quaint.2010.11.025.

Popov, S.V., Sukhanova A.A., Polyakov, S.P., 2020: Using georadar profiling techniques for the safety of transport operations of the Russian Antarctic Expedition // Meteorologiya I Gidrologiya, No 2, P. 126– 131.

Potes M., Salgado R., Costa M.J., Morais M., Bortoli D., Kostadinov I. and Mammarella I. (2017) Lake–atmosphere interactions at Alqueva reservoir: a case study in the summer of 2014, Tellus A: Dynamic Meteorology and Oceanography, 69:1, DOI: 10.1080/16000870.2016.1272787

Ravindra, R., 2001. Geomorphology of Schirmacher oasis, East Antarctica. In: Proceedings, Symposium on Snow, Ice and Glacier. Geological Survey of India, Special Publications, vol. 53, pp. 379E390.

Richter W, Bormann P. 1995. Hydrology//Bormann P, Fritzsche D. The Schirmacher Oasis, Queen Maud Land, East Antarctica, and its surroundings. Justus Perthes Verlag, Gotha, 259-319.

Report of 31 Soviet Antarctic Expedition: Novolazarevskaya scientific station, 1986. 186 pp. In Russian

Rodrigues, C. M., Moreira, M., Guimarães, R. C., and Potes, M.: Reservoir evaporation in a Mediterranean climate: comparing direct methods in Alqueva Reservoir, Portugal, Hydrol. Earth Syst. Sci., 24, 5973–5984, https://doi.org/10.5194/hess-24-5973-2020, 2020.

Sahlée, E., A. Rutgersson, E. Podgrajsek, and H. Bergström (2014). Influence from Surrounding Land on the Turbulence Measurements Above a Lake. Boundary-Layer Meteorol., 150:235–258, DOI 10.1007/s10546-013-9868-0

Sene, K. J., Gash, J. H. . and McNeil, D. D. 1991 Evaporation from a tropical lake: comparison of theory with direct measurements. Journal of Hydrology, 127, 193-217.

Singha J, Chatterjee I.: Sixteenth Indian Expedition to Antarctica, Scientific Report, Department of Ocean Development, Technical Publication No. 14, 2000. 36 p.

Shevnina E., Kourzeneva E., Dvornikov Y., Fedorova I.: Retention time of lakes in the Larsemann Hills oasis, East Antarctica, The Cryosphere Discuss., https://doi.org/10.5194/tc-2020-205, in review, 2020.

Shevnina E, Kourzeneva, E., 2017: Thermal regime and components of water balance of lakes in Antarctica at the Fildes peninsula and the Larsemann Hills. Tellus A: Dynamic Meteorology and Oceanography. 2017; 69(1). DOI:10.1080/16000870.2017

Shine K P: Parametrization of the shortwave flux over high albedo surfaces as a function of cloud thickness and surface albedo. Quart. J. Roy. Meteor. Soc. 1984; 110:747–764. DOI: 10.1002/(ISSN)1477-870X

Shuttleworth, W. J. 1993 Evaporation. In: Maidment, D.R., (ed.) Handbook of Hydrology, New York: McGraw-Hill, 4.1-4.53.

Srivastava G. P. Surface meteorological instruments and measurement practices, New Delhi : Atlantic Publ., 2009, pp. 265-289.

Stokes C. R., Sanderson J. E., Miles B. W. J. et al.: Widespread distribution of supraglacial lakes around the margin of the East Antarctic Ice Sheet, Scientific Reports, 9 (1), doi: 10.1038/s41598-019-50343-5, 2019.

Stull, R., 2017: Practical Meteorology: An Algebra-based Survey of Atmospheric Science" -version 1.02b. Univ. of British Columbia. 940 pp. ISBN 978-0-88865-283-6 .

Tanny J., Cohen S. , Assouline S., Lange F., Grava A. , Berger D. , Teltch B. , ParlangeM.B. 2008: Evaporation from a small water reservoir: Direct measurements and estimates. Journal of Hydrology, 351, 218– 229

Tietäväinen, H., Vihma, T. 2008. Atmospheric moisture budget over Antarctica and the Southern Ocean based on the ERA-40 reanalysis. Int. J. Climatol. 28, 1977–1995. DOI: 10.1002/joc.1684.

Thiery, W., I. V. Gorodetskaya, R. Bintanja, M. R. Van den Broeke, C. Reijmer, P. Kuipers Munneke, N. P. M. Van Lipzig (2012), Surface and snowdrift sublimation at Princess Elisabeth station, East Antarctica. Cryosphere, 6 (2), 841-857.

Turner, J., and Pendlebury, S. F., 2004: The International Antarctic Weather Forecasting Handbook. British Antarctic Survey, 663 pp.

Turner, J., Colwell, S.R., Marshall, G.J., Lachlan-Cope, T.A.,Carleton, A.M., Jones, P.D., Lagun, V., Reid, P.A. and Iagovkina, S. (2004) The SCAR READER project: towards a high-quality database of mean Antarctic meteorological observations. Journal of Climate, 17, 2890–2898.

Turner J, Marshall GJ, Clem K, Colwell S, Phillips T, Lu H. Antarctic temperature variability and change from station data. Int J Climatol. 2019;1–22. https://doi.org/10.1002/joc.6378

Yang, Y., Cheng, B., Kourzeneva, E., Semmler, T., Rontu, L., Leppäranta, M., Shirasawa, K. and Li, Z. 2013. Modeling experiments on air–snow–ice interactions over Kilpisjärvi, a lake in northern Finland. Boreal Environ. Res. 18, 341–358.

Verleyen E., Hodgson D., Gibson J. et al., 2012: Chemical limnology in coastal East Antarctic lakes: Monitoring future climate change in centers of endemism and biodiversity. Antarctic Science, 24(1), 23-33. doi:10.1017/S0954102011000642.

Venäläinen, A., Heikinheimo, M. and Tourula, T. 1998. Latent heat flux from small sheltered lakes. Bound-Lay Meteorol. 86, 355–377. DOI: 10.1023/A:1000664615657.

Vesala, T., Houtari, J., Rannik, U., Suni, T., Smolander, S., Sogachev, A., Launiainen, S., and Ojala, A., 2006: Eddy covariance measurements of carbon exchange and latent and sensible heat fluxes over a boreal lake for a full open-water period, J. Geophys. Res., 111, D11101, https://doi.org/10.1029/2005JD006365

Vincent, W., & Laybourn-Parry, J. (Eds.), Polar Lakes and Rivers: Limnology of Arctic and Antarctic Aquatic Ecosystems. : Oxford University Press,. Retrieved 11 Sep. 2018, from http://www.oxfordscholarship.com/view/10.1093/acprof:oso/9780199213887.001.0001/acprof-9780199213887.