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Holocene climate variability from the lake sediment core in Schirmacher Oasis region, East Antarctica: Multiproxy approach

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ABSTRACT

A 1.62 m sediment core was retrieved from one of the landlocked freshwater lakes (L-6) in the Schirmacher Oasis (SO), East Antarctica during the 24th Indian Antarctic Expedition (2004–2006). The sediment core samples were analyzed for Total Organic Carbon (TOC), Biogenic Silica (BSi), grain size and elemental concentration ratios (Mg/Ca and Mn/Fe). The sediment core represents the time period of last ~11.6 cal ka BP as ascertained by AMS ^{14}C radiocarbon dates. The sedimentation accumulation rate variation of ~13.6 cm/ka from ~11.6 to ~10 cal ka BP reveals a warm phase followed by a low sedimentation accumulation rate of ~2.9 cm/ka from ~10 ka BP to ~3.1 ka BP, indicating a cold period in the region. The sedimentation accumulation rate again increased from ~3.1 cal ka BP to recent with a maximum of ~88 cm/ka which reveals the initiation of glacier retreat or ice-free conditions in the study area. The Total Organic Carbon (TOC) is <2% from ~10 to ~3.1 cal ka BP indicating a prolonged colder phase in the study area. However, elevated TOC, BSi and Mg/Ca ratio since ~3.1 cal ka BP to recent points indicates towards ice-free conditions (continental ice sheet retreat) and subsequently high productivity in the region. Moreover, the productivity was higher at the Pleistocene–Holocene boundary as evidenced by the Mg/CA, Mn/Fe ratio and Biogenic Silica (BSi). The present study identified a colder phase (or re-advancement of continental ice sheet) during the early to mid-Holocene and initiation of ice-free or continental ice-sheet retreat during the late Holocene and their implications on the productivity changes.

1. Introduction

In general, Antarctic ice cover (permanent or temporary) significantly influences both the physical and biological processes occurring within the lakes. The temporal variation of the ice cover and ice-free conditions of the lakes vary due to the great difference in mean temperature related to the locations (Lyons et al., 2006). The extent and thickness of the ice cover are critical parameters in defining the biogeochemistry of Antarctic lakes (Wharton et al., 1993; Fritsen and Priscu, 1999) because there are lakes which are ice-covered throughout the year and while the few areas experienced ice-free lakes during the summer. In summer, Antarctica receives more solar radiation than the tropics, but shows high albedo as most of the radiation reflects back into space due to ice or snow cover (Turner et al., 2009). In contrast, Antarctic stratosphere is cold due to the lack of incoming solar radiation during winter (Turner et al., 2009), which results in more snow cover over the coastal lakes. However, the process of snow melting exposed the bare rocks and makes the regional environment warm in the ice-free areas. Antarctic Oasis is the ice-free areas in contemporary perspective. There are areas where the lakes in the coastal regions and Oasis are ice free for 3–4 months in a year and are exposed to the sun, which influences the biological productivity as characterized by the presence of diatoms and moss. The biological productivity of the Antarctic lakes is mainly regulated by the seasonal temperature variations which have been modulated through the melting of ice cover. Consequently, the biological productivity is usually high during the summer period due to the ice-free state being exposed to the sun, whereas less during the winter period being ice covered condition and less sunlight (Hodgson et al., 2004). The proxies such as grain-size analysis, Total Organic Carbon (TOC) and Biogenic Silica (BSi) were used for the paleoclimatic studies. These proxies have been used to understand the biochemistry, productivity changes and environmental behavior

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of the Antarctic lakes and surrounding ocean, (Mortlock and Froelich, 1989; Muller and Schneider, 1993; Colman et al., 1995; Kamatani and Oku, 2000; Kaplan et al., 2002; Yoon et al., 2006).

Holocene climatic variations in Antarctica have been reconstructed using a wide variety of archives like marine and lake sediments (Burgess et al., 1994; Björck et al., 1996; Hodgson et al., 2001, 2004; Bera, 2004a, 2004b; Verleyen et al., 2004, 2005; Bentley et al., 2009; Oerter, 2012), ice-cores (Steig et al., 1998; Petit et al., 1999; Masson et al., 2000) and recent temporal variations studies based on snow pits and firn cores (Li et al., 2014). The Antarctic region is known to be least influenced by anthropogenic activity, hence provides an opportunity to understand the past climatic variations. These past climatic changes are useful to understand how climate affects the flora and fauna, permanent glaciers retreat/advancement in Antarctica and its role in global climate change. Moreover, during the Holocene, the climate variation in both the hemisphere glacier retreat and re-advancement are neither strictly in the phase, nor out of phase as evidenced by the studies of glaciers retreat or readvancement in New Zealand records (Schaefer et al., 2009). The Antarctic climatic history reconstructed from long ice-cores is significant in improving our understanding of the atmosphere circulation and composition (Jouzel et al., 1989, 2007). Despite, the long ice-core studies which have been carried out to understand the long term glacial-interglacial climatic changes, the contribution of ice core studies within the Holocene from coastal areas of East Antarctica did not show promising results. The small isotopic variations and their understated climatic variations are less resolved records of the inland locations observed at coastal sites (Bromwich et al., 1998; Verleyen et al., 2011) and from the high central plateau (Masson et al., 2000). Hodgson et al. (2004) stated that the collection of reliable ice cores from coastal areas and high resolution reconstruction is difficult as ice sheet is often too dynamic and so, the lake and coastal marine sediment records are the valuable documents to use as an archive in the paleoclimatic study. Therefore, lake sediments must be targeted to get a comprehensive picture of Holocene climatic changes using a wide array of proxies. Furthermore, the Pleistocene–Holocene boundary in East Antarctic sediments must have experienced the initiation of deglaciation after the Last Glacial Maxima (LGM) glaciation in the present coastline areas (CLIMAP, 1981; Huybrechts, 1990; Hughes, 1998). But the timing of initiation of deglaciation in other regions shows different time period. The deglaciation in East Antarctic coastal regions was not synchronous as shown by the previous studies, for instance, Windmill Islands experienced deglaciation around 10,000 years (Kirkup et al., 2002); Vestfold Hills around 12,000 years BP (Fabel et al., 1997); Bunger Hills c. 30,000 years (Gore et al., 2001); Larsemann Hills at around 45,000 (Hodgson et al., 2001). Therefore, the regional glacial maxima are not in line with glacial LGM and glacier retreat or re-advancement of all the ice-free areas of Antarctica have not been understood well. The terrigenous and biogenic sedimentation in the lakes in the ice-free oasis and or in coastal areas must have incorporated the history of glacier retreat or re-advancement on the regional basis. The initiation of the biogenic or terrigenous sedimentation is the mark of the position of the lake whether the lake was experiencing ice-free conditions or behaved as a closed basin. However, the paleoclimate record from Schirmacher Oasis (SO) is being presented by the other workers based on magnetic mineral, magnetic susceptibility and loss of Ignition dataset (Phartiyal et al., 2011; Warrier et al., 2014) and the surface unconsolidated sediment mineralogical characteristics from polar ice sheets, inland lakes and coastal shelf area presented by Srivastava et al. (2013). In contrast, the present study from the SO documents the high resolution paleoenvironment information deciphered by using other multiproxy datasets such as Total Organic Carbon, grain size, elemental ratios and Biogenic silica. In

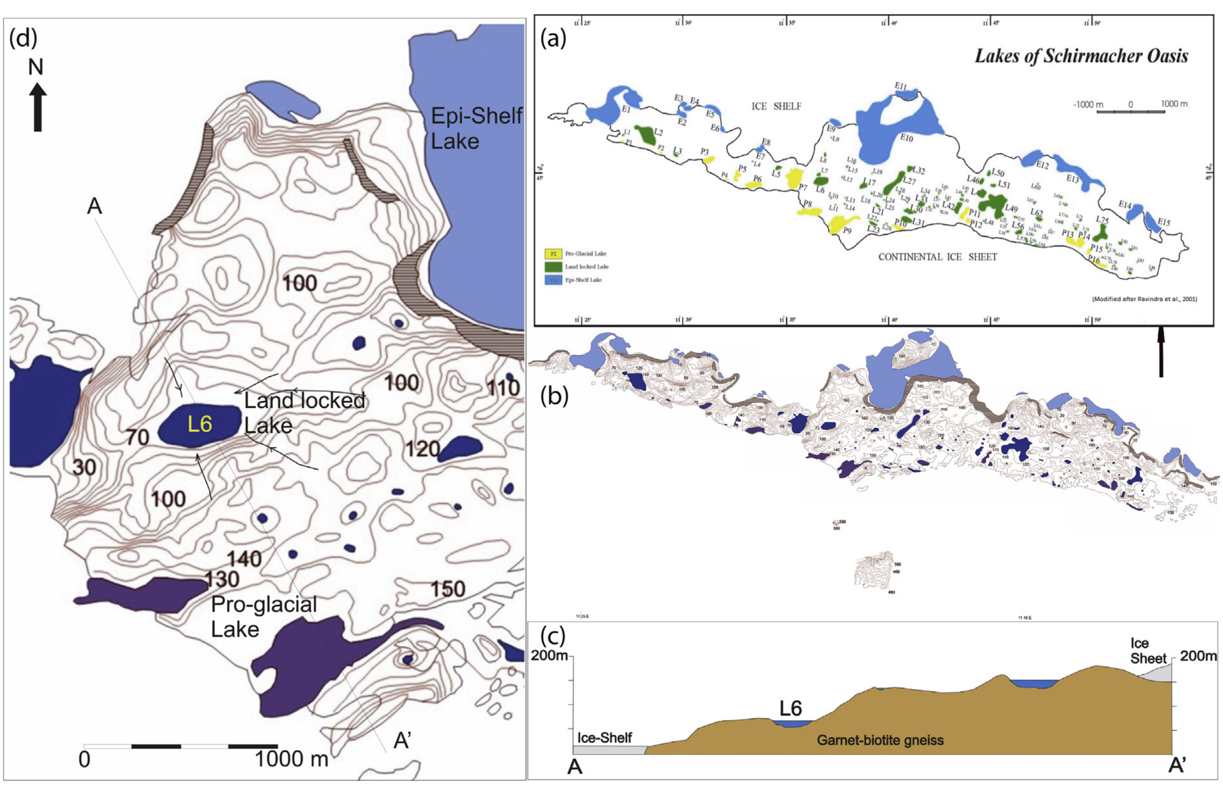

Fig. 1. a) Lakes in Schirmacher Oasis, b) Topographic Map, c) cross section and Lithology and d) location map and catchment area of L 6 lake in Schirmacher Oasis, East Antarctica.

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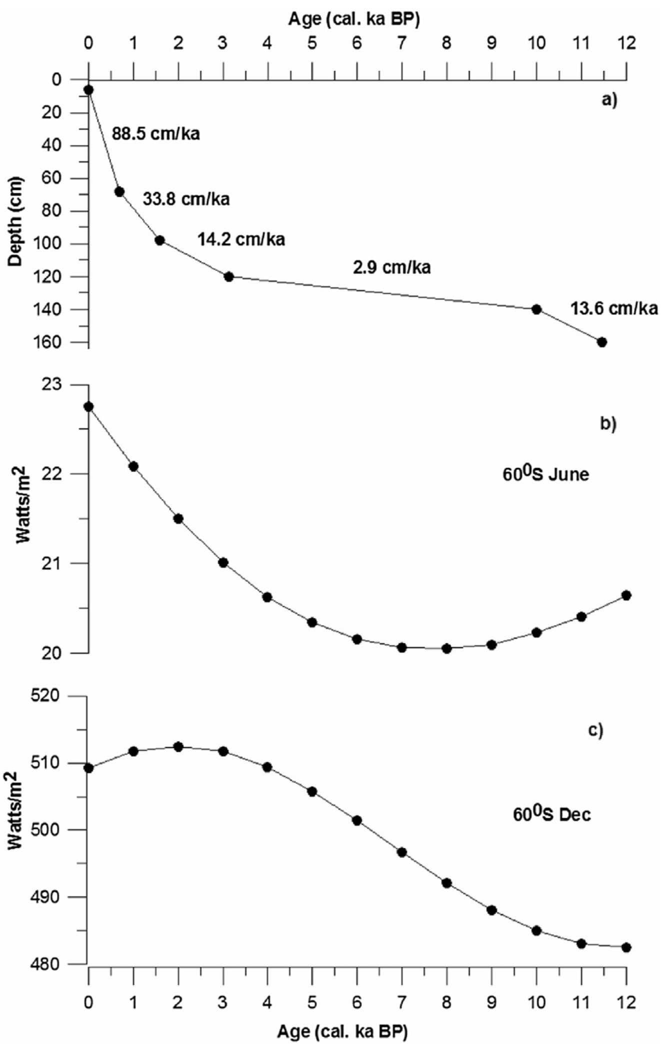

Fig. 2. a) The age-depth correlation from the Antarctic Lake sediment core L-6. Solar insolation from 60°S June (b) and December (c) from last 12 cal ka BP.

this present study, we would like to validate the spatial and temporal extension of the paleoenvironmental evolution of the lakes in SO mentioned by the former workers in our study area. Therefore, the study of the lake sediments from the presently ice-free coastal areas may help to understand the initiation of deglaciation or glaciation. In this view, the study of a sediment core from the SO is being undertaken.

2. Study area

SO is an ice-free area covering 35 km^2 (70°43′50″ – 70°46′40″ S and 11°22′40″ – 11°54′20″ E, respectively) and is situated in the Queen Maud Land region of East Antarctica (Fig. 1). The SO is ~80 km away from the open sea where the average annual temperature is −10.4 °C, and mean wind velocity is 10 m/s (Deshpande and Tripathy, 2010). SO contains 118 interspersed glacial lakes which are categorized into three different types, such as proglacial, epishelf and land locked lakes (Ravindra, 2001). The aerial photographs of the SO evidenced the snow/ice cover in the eastern part of the SO, which was reduced from 1939 to 1984 (Bormann and Fritzsche, 1995; Lyons et al., 2006). Most of the lakes of SO were ice free for a period in January/February, and ice cover does not exceed more than 2 m thick (Hermichen et al., 1985). The land-locked lakes in the SO are mostly fed by the glacial meltwater released from the continental ice sheets, situated at the southern part of the oasis. These lakes receive sediments from their adjacent areas by the melt water (from continental ice sheet and snow melt) and the wind, therefore, of prime interest to understand the past climatic variations. In this vein, the present study describes the Holocene depositional history and the onset of deglaciation, or glaciation of SO using a sediment core from one of the landlocked lakes. We used BSi, sand (%), TOC and elemental concentration ratios (Mg/Ca and Mn/Fe) results for the interpretations.

A 1.62 m sediment core was retrieved from a land locked lake assigned the name L-6 (Lat: 70°45′21.4″ S and Long: 11°35′52.6″ E; Fig. 1) in the austral summer of 2004–2006 during the 24th Indian Scientific Expedition to Antarctica. The sediment core was sub-sampled at 2 cm interval in the field lab. The lithological section shows that the top sediment core section represents the algal mat growth along with fine grain sediments. The middle part of the sediment core shows the silt and clay. The sand and moss root contribute to the bottom section of the core (Fig. 3).

2.1. AMS ^{14}C dating

Accelerator Mass Spectrometer (AMS) radiocarbon (^{14}C) ages of the organic carbon from 6 sediment samples were obtained from the National Ocean Sciences Accelerator Mass Spectrometry (NOSAMS) in the Woods Hole Oceanographic Institution, USA. The raw radiocarbon ages were calibrated using the online CALIB 7.0 program and SHcal13 curve for a Southern Hemisphere terrestrial sample (Reimer et al., 2009) (Table 1).

Table 1
Radiocarbon Dates of Core L-6.

Accession (Lab no.)#	Sample depth (cm)	Material dated	$\delta^{13}C$ (%)	Conventional age (years)	Corrected age (years)	Cal. Corrected age (years) BP with 2σ	Cal. Corrected age (ka BP)
OS-85419	6	Sediment Organic carbon	−8.04	640	0	0 ± 0	0
OS-85510	66	Sediment Organic carbon	−7.51	1460	820	700 ± 38.5	0.70
OS-85412	98	Sediment Organic carbon	−7.36	2340	1700	1586 ± 98	1.58
OS-85413	120	Sediment Organic carbon	−10.81	3660	3020	3125 ± 98	3.12
OS-85429	140	Sediment Organic carbon	−23.35	9590	8950	10,000 ± 194.5	10.00
OS-85430	160	Sediment Organic carbon	−20.58	10,650	10,010	11,468 ± 117.5	11.46

2.2. TOC analysis

The samples were oven dried at 50 °C and powdered for Total Organic Carbon (TOC) analysis. The powdered samples of 100 mg were treated with 2 N HCL to remove the inorganic carbon. The TOC was estimated using the Shimadzu TOC-VCPN analyzer. The precision of TOC analysis is 0.1%.

2.3. Particle size analysis

The grain-size analysis was performed using the method described by Krumbein and Pettijohn (1938) in which 5 gm oven dried sediment sample were soaked in the distilled water for overnight. The water was decanted next day, and then sodium hexametaphosphate was added to keep the samples again overnight. Hydrogen peroxide (30%) was added and again retained overnight and then next day the sample was sieved using a 63 μm sieve to separate the coarser sand fraction from finer silt and clay. The sand (>63 μm) was collected in an empty beaker and weighed after drying. The collective weight of silt and clay was calculated subtracting the sand weight from the total weight of the sediment taken. Hence, sand and silt-clay percentage were tabulated for all samples.

2.4. Elemental analysis

The elemental analyses carried out in this study on 2–4 cm interval were performed using Atomic Absorption Spectrometer attached with Graphite Furnace. The bulk samples were digested with hydrochloric acid as initial digestion. Then samples were refluxed and finally digested with repeated additions of nitric acid and hydrogen peroxide, following EPA method 3050B for acid digestion of sediments. In the processed samples, Calcium (Ca), Magnesium (Mg), Manganese (Mn) and iron (Fe) were determined through Thermo Solar M6 Atomic Absorption Spectrometer. Calibration standards were prepared using high purity single element standard manufactured by Inorganic Ventures, Christiansburg, VA, USA. For the digestion of sediment samples, suprapure chemicals were used, made by Merck (Germany). For the verification of analysis, Standard Reference Material 2702, inorganic in marine sediments, obtained from National Institute of Standards and Technology, USA were digested employing EPA method 3050B for acid digestion of sediments, sludge and soils. The RSD of the calibration standards, SRM and samples varied from 0.1 to 1.5% for Ca, 0.1 to 1.0% for Mg, 0.01 to 5.6% for Mn and 0.1 to 7.6% for Fe.

2.5. Biogenic-silica analysis

Biogenic Silica (BSi) was measured by the wet alkaline extraction method described by Mortlock and Froelich (1989) and Muller and Schneider (1993). Approximately 10 mg of powdered sediment was dissolved using 30 ml of 1 N NaOH solution in a 50 ml polypropylene tube. The tubes were oven dried at 85 °C for 5 h. Dissolved silica in diluted samples was measured using molybdate blue spectrophotometric method.

3. Sediment stratigraphy and chronology

The lithological log of the studied core represents the five major sedimentary units (Fig. 3). Unit 1 from 162 to 160 cm core depth clearly shows the presence of moss roots (Singh et al., 2012) containing less sand and relatively high TOC (%). This moss roots column was followed upward by sand continues from 160 to 142 cm in Unit 2. Unit 2 is characterized by high sand percentage (5%–70%), low TOC and decreasing trend in biogenic silica. Further, in Unit 3 the presence of fine silt from 140 to 90 cm, and in unit 4 fine silt with the algal mat from 90 to 44 cm was observed. Unit 5 as the upper part (<44 cm) of the core represents thick algal mat continuation evidenced that the study area experienced the light penetration to the surface of the sediment; it allowed the biological productivity of the lake system and inferred that the lake was not

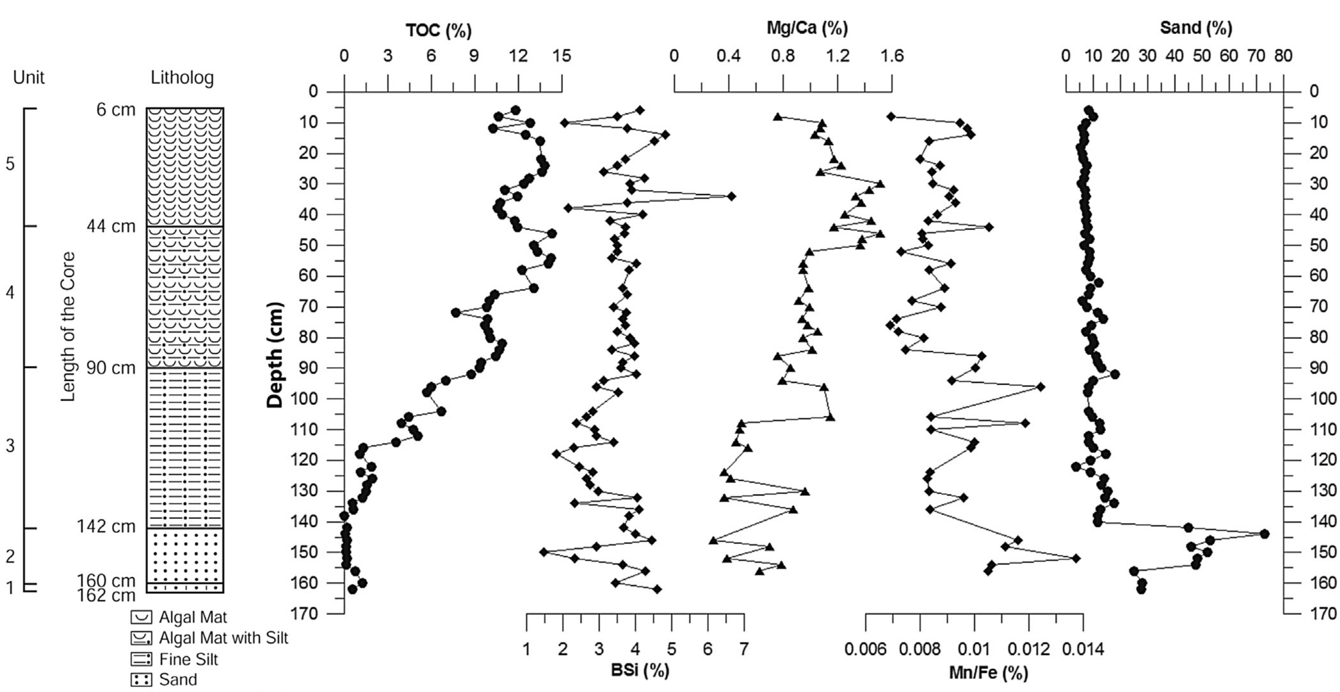

Fig. 3. The lithological log, TOC, BSi, Mg/Ca and Mn/Fe ratios variation with the depth of the Lake L-6 sediment core.

glaciated or experienced the ice-free environment. Hence, the Units 4 and 5 as shown in (Fig. 3) the stable lake system condition which enhanced the biological productivity due to the light penetration and the continuous sedimentation from the catchment area provides enough nutrient to use in organic production.

The AMS radiocarbon dating shows that the ~1.62 m length core represents ~11.6 cal ka BP (Fig. 2a; Table 1). The age-depth relationship (Fig. 2a) provided the sedimentation accumulation rate varies from ~88 cm/ka to ~2.9 cm/ka. The sedimentation accumulation rate from ~11.6 to ~10 cal ka BP (Pleistocene–Holocene Boundary) was 12.1 cm/ka and 2.9 cm/ka from ~10 to ~3.1 cal ka BP (early-mid Holocene). During the late Holocene, sediment accumulation rates in Lake L-6 show a clear increasing trend to present (Fig. 2a). Further, calculated accumulation rates were to 14 cm/ka from ~3.1 to ~1.6 cal ka BP, 34 cm/ka from ~1.6 to ~0.7 cal ka BP and 88 cm/ka from ~0.7 cal ka BP to recent. The core top sample was dated 640 years BP (Table 1). The 640 years BP age was subtracted from each radiocarbon ages to attain the reservoir corrected ages for this core, and then the ages were calibrated into calendar years (cal ka BP). The reason has been explained by studying (Wagner et al., 2004 and reference therein) the lake which was permanent ice covered in the past decades and may show no influence of the nuclear bomb ^{14}C. The old carbon could have from the glacial meltwater remnants if the depleted ^{14}C glacial meltwater streams travel a short distance in the catchment of this lake would have led to equilibrium values with gas exchanges with the atmosphere (Doran et al., 1999; Wagner et al., 2004). Simply, it has been suggested that the reservoir age effect would be smaller if the glacial melt water covers the less distance and would be the higher reservoir age effect if the glacial melt water cover a long distance (Wagner et al., 2004). However, the ^{14}C results from this core were not able to reconstruct the old carbon flux to and from the lake. Therefore, the core top age has been subtracted from the down core ages. The reasons and causes have been well explained in the earlier studies from East Antarctica (Wagner et al., 2004).

The sedimentation accumulation rate in this core is in good corroboration with the solar insolation curve in 60°S during June (winter) and December (summer) (Fig. 2b and c) through mid-late Holocene. The Southern Hemisphere insolation value has been taken from Berger and Loutre (1991). The insolation curve during the winter period also supports the deglaciation (warming phase), started from ~4 cal ka BP with the values ranging from 20.5 to 22.7 W/m^2 besides summer solar insolation value which is almost consistent and attains a maximum value of approximately 510 W/m^2. The summer insolation values range from 482 to 510 W/m^2 and the winter solar insolation values range from 20.06 to 22.76 W/m^2 within the ~12 ka BP. The winter solar insolation curve remains more consistent with the sedimentation curve of the studied lake and suggests that the climatic variation in the SO is being enforced by the solar activity of high latitude southern hemisphere within the Holocene.

4. Results

The TOC varied from 14.27% to 0.01% in the core (Fig. 4). The TOC ranged 1.24%–0.11% during ~11.6 to ~10 cal ka BP. It remained low (1.96%–0.01%) from ~10 to ~3.1 cal ka BP, whereas higher values of TOC were noticed (14.27%–1.08%) during ~3.1 cal ka BP to recent (Fig. 4).

The BSi values range from 6.64% to 1.47% in the core (Fig. 4). The BSi varied 4.95 to 1.47% from ~11.6 to ~10 cal ka BP. It remained low (4.0%–2.32%) ~10 to ~3.1 cal ka BP, whereas higher values were found (6.64%–1.83%) from ~3.1 cal ka BP to recent (Fig. 4).

The grain size distribution shows a dominance of the sand over silt and clay during the early Holocene (~11.7 to ~10 cal ka BP) (Fig. 4). Silt and clay are predominant during the rest of the period in the Holocene. Sand (%) ranges from 72.91 to 3.80%, while silt and clay range from 96.20 to 27.10% (Fig. 4).

The elemental concentration ratio of Mg/Ca ranges from 0.28 to 1.51% and Mn/Fe values from 0.0116 to 0.0069%. The Mg/Ca and Mn/Fe ratios were higher over Pleistocene–Holocene boundary (~11.6 to ~10 cal ka BP). Mg/Ca values were higher in the upper part of the core which indicates the late Holocene (~3.1 cal ka BP to recent) (Fig. 4). Mn/Fe ratio showed slightly low values in the late Holocene (~1.5 cal ka BP to recent). In context, Mg/Ca, and Mn/Fe ratios show low values during the early-mid Holocene time period (~10 to ~3.1 cal ka BP) (Fig. 4).

5. Interpretation

Based on the generated dataset the present study can be divided into three phases which describe the productivity variations during the Pleistocene–Holocene boundary, early-mid Holocene and late Holocene periods.

5.1. Pleistocene–Holocene boundary (Depth 162–140 cm; ~11.6 to ~10 cal ka BP)

The age-depth relationship (Fig. 2a) shows the sedimentation rate of 13.6 cm/ka from ~11.6 to ~10 cal ka BP. The lithological section of the studied core (Fig. 3) represents the moss root from 162 to 160 cm (Unit 1 in Fig. 3) (Singh et al., 2012) with less than 30% sand. This presence of moss roots during this time period confirms that the lake was ice free and the deposition of soft biogenic matter under the lacustrine conditions. Sediment flux might have increased to the lake from both the biological and terrigenous sources. These moss roots column were followed upward by the sand column, which continued from 154 to 142 cm (72–45% sand) (Unit 2 in Fig. 3) corresponding to ~11 to ~10 cal ka BP. It infers that the lake might have received a high amount of sediment carried by glacial melt water which eventually suppressed the growth of underlying algal mat over the onset of Holocene boundary. The grain size distribution shows a dominance of sand over silt and clay during the Pleistocene–Holocene boundary (~11.6 to ~10 cal ka BP) (Fig. 4). The lower part of the core consists of sand (Units 1 & 2 in Fig. 3) with a low percentage of silt and clay which corresponds to fluvioglacial deposition due to continental ice-sheet retreat in the study area. During the onset of Holocene TOC shows a lower concentration (<2%) from ~11.0 to ~10 cal ka BP, which may be due to the high sand deposition during this period. The more concentration of sand allowed oxygen to percolate in the sediment and hence decomposed the organic carbon that released in the form of CO_2 to the atmosphere (Govil et al., 2012). It is also confirmed by the high Mn/Fe ratio, which shows the reducing conditions at the down core sediments (Fig. 4). Reducing conditions are the results of oxygen consumption or utilization by the organic matter remineralization and caused the release of Mn and Fe in the water column (Nealson and Saffarini, 1994; Naeher et al., 2013). After oxygenation, the Mn and Fe got deposited and preserved in the sediments. However, the Mn precipitation got increased due to the catalysis by Mn-oxidizing bacteria in the sediments (Diem and Stumm, 1984). The high concentration of sand allowed more oxygen percolation through the pores which eventually decomposed the TOC and hence the low values of TOC may have been incurred in the sediments. Whereas, BSi values (4.9–1.4%) and a ratio of Mg/Ca confirm the high productivity during the Pleistocene–Holocene boundary (~11.6 to ~10 cal ka BP) (Fig. 4). The reason could be the high terrigenous input, which might have allowed more nutrients to increase the diatom production and

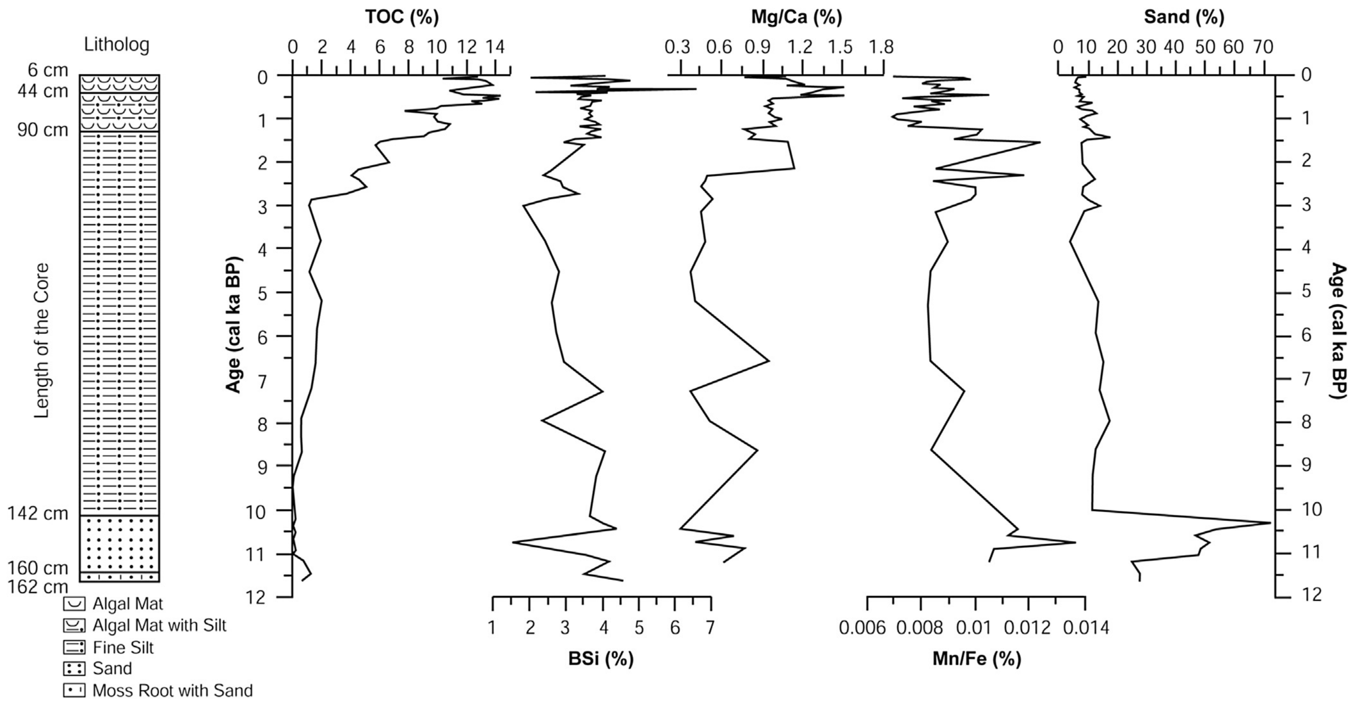

Fig. 4. The Lithological log, TOC, BSi, Mg/Ca and Mn/Fe ratios variation with the chronological sequence of the Lake L-6 sediment core.

subsequently recorded as the more concentration of BSi preserved in the lake sediments. Due to weathering, elements like Mg and Ca were leached out from the catchment rocks and was subsequently eroded away and deposited in the lake basin by fluvial and/or aeolian agents (Boyle, 2001; Mugler et al., 2010). It is further supported by the excellent preservation of BSi and Mg/Ca ratio, which reciprocates with <30% of sand refers the enrichment of biogenic sedimentation over the terrigenous input during ~11.6 to ~11 cal ka BP time period (for almost 600 years). In contrast, the time period of ~11 to ~10 cal ka BP (onset of the Holocene) shows more terrigenous input in the form of sand (>30%) over the biological productivity sedimentation for almost 1000 years. It may refer as terrigenous dilution effect over the biogenic sedimentation for which the BSi percentage and Mg/Ca ratio show a proper dip (Fig. 4) in this period. A significant contribution from the terrigenous input to the core site was remarkably evident in shifting of environmental changes during/at the onset of the Holocene. The relative concentrations of these elements also suggest the high runoff of the weathered materials which imply the lake was not covered by the continental ice sheet, and hence more sedimentation leads to overall increased productivity. The lake water level might have been high and experienced with positive water balance because lake might have received an enormous quantity of fresh melt water from the southern continental ice sheet in SO. This positive water balance during warming time period is evidenced by the high percentage of sand deposition to the site which, along with the presence of algal moss root further postulates that lake was ice free. On the other hand, insolation data of the 60°S summer insolation curve show the minimum constant value (Fig. 2c); in contrast, the winter insolation values which somewhat show the decreasing trend from 20.94 to 20.41 W/m2 (Fig. 2b). It suggests that the Pleistocene–Holocene boundary experienced a comparatively decreasing trend of temperature during the winter of the East Antarctica, and insolation data is not compatible with the present study core data.

5.2. *Early-mid Holocene (Depth 140–120 cm; ~10 to ~3.1 cal ka BP)*

The lithology at the depth of 140–120 cm contains the fine sand (<20%) (Unit 3 in Fig. 3) marked the early-mid Holocene period (~10 to ~3.1 cal ka BP), the TOC and BSi show low values (1.96%–0.01% and 4.0% to 1.83%, respectively). The lower values of BSi indicate a less production of siliceous algae, such as diatoms. Furthermore, the elemental concentration ratios of Mg/Ca which also show the sign of relatively low productivity. The low Mn/Fe ratios, also suggests the low oxygenated bottom water of the lake. This low oxygenated water probably occurred due to the less meltwater flux from the glacier and the catchment area. However, interestingly the BSi exhibit average value of 3.49% with minimum and maximum values of 2.32% and 4.1%, respectively, while Mg/Ca ratios show the mean value of 0.6% with a minimum and maximum value of 0.29% and 0.96%, respectively. These data document moderately high values for both BSi and Mg/Ca ratios during early Holocene ~10 to ~6.6 cal ka BP (Fig. 4). It could be due to the lake took a long time to undergo the ontogenetic process, which therefore describes the lake productivity might have taken the period to equilibrate with the overlying continental ice sheet. From ~6.6 to ~3.1 cal ka BP the BSi value average is 2.49% and minimum and maximum 1.83% and 2.82%, respectively, and Mg/Ca ratio average 0.43% and minimum to maximum 0.37% and 0.48%, respectively. These values were comparatively lower than Early-Middle Holocene, which documents the weak growth of diatoms and low nutrient supply, and supports the cooler climatic conditions. Furthermore, during this period, the L-6 lake received relatively less amount of sediment with the sediment accumulation rate of ~2.9 cm/ka (Fig. 2a) from ~10 to ~3.1 cal ka BP. It suggests that the lake was covered partially or entirely with a continental ice sheet as it might have presided over this lake towards the northern part of the SO. Consequently, the lake basin was partially closed therefore did not receive much clastic as well as biogenic sediments during this interval for almost 7000 years from the barren catchment area, and the lake was acted as a glacial lake. This period must have evidenced the arid basin and harsher climatic condition due to low energy climatic and environmental conditions. The <20% sand deposition also supports a low-energy depositional environment of the basin. This is sustained by the evidence of the winter solar insolation at 60°S which shows the values ranges from 20.1 to 20.6 W/m^2 and the summer insolation 488.13–509.34 W/m^2 in East Antarctica (Fig. 2b and c). It clearly infers that the winter temperature during early-mid Holocene was lower compared to Pleistocene–Holocene boundary and late Holocene. The lower temperature during the winter for 7000 years might have forced the continental ice sheet to extend towards the northward direction of the SO. Furthermore, a rapid decrease in the sand percentage (Fig. 4) also supports the less terrigenous input and eventually the low sediment accumulation rate. Therefore, the significant contribution of this low sediment accumulated to the core site must have been from the fluvioglacial deposits. It may be due to low availability of nutrients. The low availability of nutrients in the water column caused the less production of organic matter as evidenced by low TOC values during early-mid Holocene. Another reason could be the low TOC and BSi, which infer the low photosynthetic activity due to low light penetration over the surface of the lake.

5.3. Late Holocene (Depth 120–06 cm; ~3.1 cal ka BP to recent)

The lithology from the depth of 120–90 cm showed fine sand and varied from 90 to 44 cm with an algal mat with silt. Algal mat continued from 40 to 6 cm (Unit 3; 4 and 5 in Fig. 3) marked the late Holocene period, which documents warming as continental ice-sheet retreat or onset of deglaciation may be characterized in the SO, which started rapidly from the boundary of mid-late Holocene (~3.1 cal ka to recent). It is reflected by the increasing trend of sediment accumulation rate from ~14 cm/ka to ~88 cm/ka with variation in winter solar insolation curve, which ranges from 20.5 to 22.7 W/m^2 and caused the lengthening of the ice-free regions (Fig. 2a and b). The gradual increase in the solar insolation describes the stepwise warming through the temperature variation within ~3.1 cal ka BP period. Increased temperature in the east Antarctica caused to the warm environment and must have forced the continental ice sheet to retreat towards the southern edge of the SO. The sediment accumulated at the rate of 14 cm/ka during ~3.1 to ~1.5 ka BP, 34 cm/ka during ~1.5 to ~0.7 ka BP and ~88 cm/ka during ~0.7 cal ka BP to recent have occurred to the core site. This stepwise increase in sediment accumulation and stepwise warming indicate that the core site received greater snowmelt water and increased aquatic biological productivity triggered by the degree of solar insolation (Fig. 2).

The TOC value shows an increasing trend in productivity as value ranges from 1.08% to 14.27% during ~3.1 cal ka BP to recent (Fig. 4). Simultaneously, the BSi values ranging from 1.83% to 6.64% during ~3.1 cal ka BP to recent (Fig. 4) also confirm the higher productivity compared to early-mid Holocene record. The age-depth correlation (Fig. 2a) also shows stepwise sediment accumulation in the core from lower to higher sedimentation which could be more biogenic over terrigenous input. During this period, the lake was, therefore, open due to the retreat of the continental ice sheet towards the southern side of the SO. The increased organic matter production shows in situ aquatic sources to this site. Furthermore, the lithological section of the upper part of the core indicates the presence of algal mat which could only be possible due to the excellent preservation and high biogenic sedimentation in the upper part of the core strengthening the high biological productivity (Figs. 2a and 4). The higher concentrations of elemental ratios of Mg/Ca also show the more paleoproductivity during this period. The Mg/Ca and Mn/Fe ratio increased from ~3.1 to ~1.4 cal ka BP and are well correlated with the productivity and oxygenation of the bottom water lake. Interestingly, Mn/Fe ratio is showing slightly lower concentration from ~1.4 cal ka BP to the recent which may indicate the later stage of less oxygen in the lake bottom water. For an explanation, at the starting time of deglaciation around ~3.1 cal ka BP, the lake might have received the high runoff in summer and attained high terrigenous input from the surrounding areas. Once the continental ice sheet had retreated within 2000 years, the melt water from the continental ice sheet was merely feeding this lake from the south side of SO as it can be seen due to a low sand percentage. The only possible way to receive the runoff and terrigenous input was from the surrounding snow meltwater through Aeolian transportation. However, terrigenous input was not only the primary cause for the high sedimentation accumulation rate, rather it was due to the high biological production as indicated by the presence of algal mat in the upper part of the core. Moreover, generally during the late Holocene, the lake has received high runoff, terrigenous input and prevailing conditions for high biological production. Hence, the lake attained the high paleoproductivity as it remained open to the environment.

6. Discussion

6.1. Pleistocene–Holocene boundary (~11.6 to ~10 ka BP)

The present study documents that Pleistocene–Holocene boundary experienced warming phase based on the presence of moss roots, elevated TOC (%) and BSi (%) and less sand (%) (Unit 1 in Fig. 3) from the western part of SO. This corroborated with other records in SO as well as other areas of Antarctica (Fig. 5). Phartiyal et al. (2011) and Warrier et al. (2014), data based on loss of ignition, magnetic susceptibility, environmental magnetic properties and inter-parametric ratios from the dry lake sediment and landlocked sediment cores from the central and eastern part of the SO, respectively. It also verifies the deglaciation phase of early Holocene. Phartiyal et al. (2011) show that the SO was dominated by glaciated landlocked lakes before Pleistocene–Holocene boundary (~13–12.5 ka BP); pro-glacial lakes came into existence due to the glacier retreat in Early Holocene warming (~11.5 ka BP) in the southern part of the SO. Also, Warrier et al. (2014) also recorded the onset of relatively warm climatic conditions at the Pleistocene–Holocene boundary (~12.55–9.88 cal ka BP). However, the present study shows that the sand (%) was abruptly high in unit 2 (Fig. 3) due to high meltwater flux from the southern part of SO to the core site. Unit 1 and 2 (Fig. 3) show the time lag between the biological sedimentation and the clastic sedimentation. It may be explained by ablation of glacier ice, which allows firstly for the organic deposition (removal of ice and snow cover over the lake) and with the time lake must have received the clastic sedimentation by meltwater flux through the streams. Though the present lake sediment core has been restricted up to ~11.6 cal ka BP, we may infer that the deglaciation in the SO was started before ~11.6 cal ka BP, as documented by Phartiyal et al. (2011). Overall, the different proxy based datasets from SO confirms the Pleistocene–Holocene boundary was undergoing deglaciation. The initiation of the warming in the SO (~11.5 cal ka BP or prior) is correlated with the closing of Antarctic cold reversal time at ~12.4 cal ka BP, as evidenced by ice core studies from East Antarctica (Morgan et al., 2002; Watanabe et al., 2003). The other studies also evidenced the deglaciation at the Pleistocene–Holocene boundary as recorded by a grounding-line retreat in the Lazarev Sea (Gingele et al., 1997); margins of the Amery Oasis (Wagner et al., 2004); Vestfold Hills (Fabel et al., 1997); and Windmill Islands (Kirkup et al., 2002; Cremer et al., 2003). Moreover, it has been explained by the gradual retreat of the continental ice sheet towards the landmass from the continental shelf (Evans et al., 2005; ÓCofaigh et al., 2005).

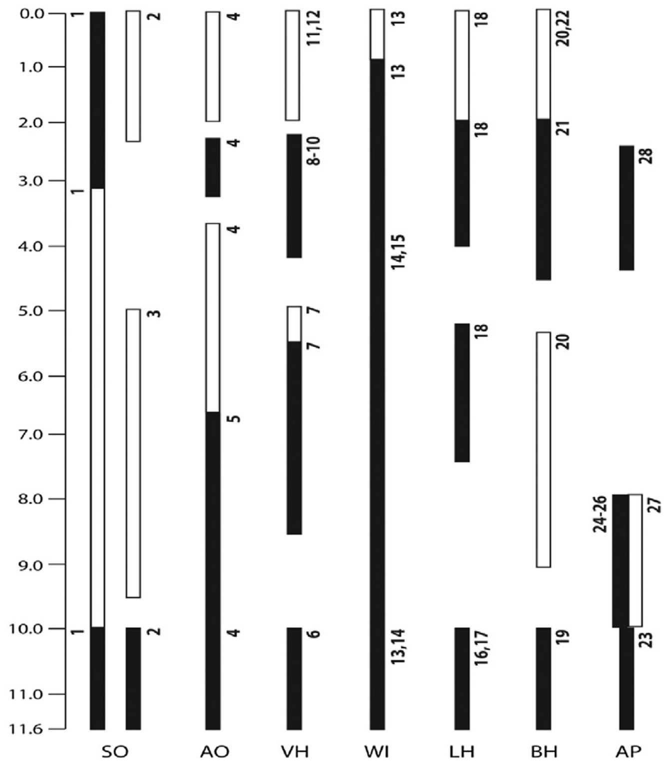

Fig. 5. The diagram representing comparative studies of Holocene Antarctic paleoclimate; Schirmacher Oasis (SO) – (1) Present study, (2) Warrier et al. (2014), (3) Phartiyal et al. (2011); Amery Oasis (AO) – (4) Wagner et al. (2004), (5) Cremer et al. (2007); Vestfold Hills – (6) Fabel et al. (1997), (7) Gibson in Verleyen et al. (2011), (8) Roberts and McMinn (1999), (9) Pickard et al. (1986), (10) McMinn et al. (2001), (11) Fulford-Smith and Sikes (1996), (12) McMinn (2000); Windmill Islands – (13) Kirkup et al. (2002), (14) Cremer et al. (2003), (15) Hodgson et al. (2003); Larsemann Hills – (16) Hodgson et al. (2001), (17) Hodgson et al. (2004), (18)Verleyen et al. (2004); Bunger Hills – (19) Gore et al. (2001), (20) Verkulich et al. (2002), (21) Melles et al. (1997), (22) Verkulich and Hiller (1994); Antarctic Peninsula – (23) Pudsey et al. (1994), (24) Bentley et al. (2005), (25) Smith et al. (2007), (26) Roberts et al. (2008), (27) Domack et al. (2005), (28) Rosqvist and Schuber (2003). White bar represents the colder period, while dark bar suggests the warmer period.

The early Holocene warming phase of the present study also supports the evidence from Larsemann Hills and other East Antarctic ice-free Oasis records, marking the retreat of glaciers, which caused the lengthening of ice-free environment to the lakes (Hodgson et al., 2001, 2004; Gore et al., 2001; Govil et al., 2011; Phartiyal et al., 2011). The Early Holocene warming conditions have also been deciphered from ice-cores (Steig et al., 2000; Mayewski et al., 2009). Furthermore, according to the record from Antarctic Peninsula (AP), the deglaciation was started at ~18.5 cal ka BP and in other areas, the initiation of deglaciation or the ice-sheet retreat occurred around ~14–13 cal ka BP (Evans et al., 2005; Heroy and Anderson, 2005). However, Pudsey et al. (1994) suggested a deglaciation around ~12 cal ka BP off Anvers Island. In present work Pleistocene–Holocene Boundary (~11.6 ka to 10 ka BP) evidenced the warming in SO.

6.2. *Early-mid Holocene ~10 to ~3.1 cal ka BP*

The present study indicates that the SO was colder in this time frame which is in corroboration with other studies (Fig. 5), such as records from AP, which also documented the retreat of George VI Ice Shelf on the west side of AP during ~9.5 to ~7.9 cal ka BP (Bentley et al., 2005; Smith et al., 2007; Roberts et al., 2008). But the eastern side of the AP did not indicate any sign of deglaciation (Domack et al., 2005). The study from Amery Oasis the slight warming was evidenced based on the minor increase in lake, organic content during the Early Holocene from 10.2 ka to 6.7 ka BP (Cremer et al., 2007) and this was followed by cold conditions from 6.7 ka to 3.7 ka BP (Wagner et al., 2004). In the Bunger Hills, cold and dry conditions prevailed from 9 ka to 5.5 ka BP, which shows the less meltwater flux resulted in ice cover over the lakes (Verkulich et al., 2002). The available data from the coastal sediments with high TOC, high C/N ratio and low abundance of ice related diatoms documents the marine optimum from 9.4 ka to 7.6 ka BP followed by cold ocean conditions from 7.6 ka to 4.5 ka BP (Kulbe et al., 2001). In contrast, the other study by Ainley et al. (2006) shows the marine climate optimum from 7.5 ka to 5.5 ka BP based on snow petals feeding habit. In the Vestfold Hills, warm period noticed from 8.5 ka to 5.5 ka BP followed by a rapid cooling period for over the next 500 years (Gibson unpublished results in Verleyen et al., 2011). On the other hand, paleoclimatic inferences from Vestfold Hills have been hampered due to isostatic rebound and the emergence of low altitude lakes isolation from the sea during the early to mid-Holocene time period (Roberts and McMinn, 1999). In the Windmill Islands, open water and sea ice condition inferred based on diatom assemblages between 10.5 ka and 4 ka BP suggest the cool summer conditions (Cremer et al., 2003; Hodgson et al., 2003). The earlier study of Larsemann Hills suggests that a period of warming and more productive during the interval of ~7.4 to ~5.2 cal ka BP (Verleyen et al., 2004). The elemental concentration ratios in the present study document low terrigenous input and less runoff, which may imply that the L-6 lake water level must have been low. As the continental ice sheet covered the lake for an extended time period, so it must have reduced the water balance caused less nutrient supply and high albedo during summer in and surroundings of the lake. The previous study from SO also stated that the climate was colder during 9.5–5 ka BP (Phartiyal et al., 2011) based on the magnetic mineral dataset, and our data from another proxy as well is in accordance with the earlier study. This emphasizes on the colder phase of climate or re-advancement of the continental ice sheet in the SO in early-mid Holocene time. However, there are time differences of colder period or glaciations within the early-mid Holocene from other studies in East Antarctic oases (Verkulich et al., 2002). The present work concludes the onset of glaciation at the boundary of ~10 cal ka BP, which lasts up to ~3.1 cal ka BP (Early-mid Holocene) in SO for over almost 7000 years.

6.3. *Late Holocene ~3.1 cal ka BP to recent*

This time period documents warming in SO as continental ice-sheet retreat or onset of deglaciation started rapidly from the boundary of mid-late Holocene (~3.1 cal ka to recent). The stepwise increase in sediment accumulation rate and enhanced biological production in the lake probably refer to a warm phase. Additionally, the other studies from Lutzow-Holm Bay region in Dronning Maud Land also suggests the warming occurred due to the removal of regional ice mass and melting of ice and henceforth concludes an isostatic rebound in the area from 4.7 ka to 3 ka BP (Okuno et al., 2007). In earlier studies (Fig. 5), it was observed the presence of 'Mid-Holocene Hypsithermal' (MHH) with the evidence of rapid sedimentation and high organic productivity in lake sediments from the South Shetland Islands (Schmidt et al., 1990; Björck et al., 1996) and Subantarctic South Georgia (4.4–2.4 cal ka BP; Rosqvist and Schuber, 2003). In the Bunger Hills, a similar stepwise increase in the primary production was documented between 4.7 and 2 ka BP (Melles et al., 1997). The coastal areas of East Antarctica, such as Larsemann Hills, also exhibit the warm period from ~4 ka BP to recent time with the initiation of biogenic sedimentation (Govil et al., 2011). Another study from Larsemann Hills shows warm

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period from 4 ka to 2 ka BP resulted in the increase of water level in the lakes (Verleyen et al., 2004). The warming at the onset of late Holocene with other parts of East Antarctica is in the match due to high precipitation and warmer climatic conditions (Goodwin, 1998; Ingolfsson et al., 1998). In Amery Oasis, the warmer condition was reported based on increased organic deposition from 3.2 ka to 2.3 ka BP (Wagner et al., 2004). The other studies also document the warmer phase initiated in the mid-late Holocene boundary; as, for example, Vestfold Hills experienced such event during the 4.2 ka to 2.2 ka BP, which resulted in the freshwater discharge in lakes recording the low salinity and humid conditions (Pickard et al., 1986; Roberts and McMinn, 1999; McMinn et al., 2001). In the Windmill Islands, humid and open water conditions caused more biological sedimentation from 4 ka to 1 ka BP (Kirkup et al., 2002). Furthermore, marine sediments also proved as a period of reduced sea-ice coverage, and greater primary production, along with an increase in melt water-derived sedimentation (Okuno et al., 2007). However, a neoglacial cooling event from 2 ka Bp to Recent was documented in a few regions of Antarctica. Such neoglacial cooling occurred in the Larsemann Hills (Verleyen et al., 2004), Amery Oasis (Wagner et al., 2004), Vestfold Hills (Fulford-Smith and Sikes, 1996; McMinn 2000), Windmill Islands (Kirkup et al., 2002), Bunger Hills (Verkulich and Hiller, 1994; Verkulich et al., 2002) with some fluctuations in various proxies during the last 2000 years and hence inferred as a cooling event. In the Dronning Maud Land region, a single study from Schirmacher Oasis witnessed a cold and dry climate based on the increase in magnetic values and a decrease in magnetic grain size from ~2.3 ka BP (Warrier et al., 2014). Since the data based on mineral magnetic and mineral grain size, there is no direct evidence of the productivity of this area. Our dataset (higher TOC value) gives a confirmatory evidence of the higher productivity continuing till Recent, which eventually provides evidence for warming event. High resolution studies of more sediment cores from the Lutzow-Holm Bay region and Schirmacher Oasis can lead to a constructive conclusion whether the neoglacial cooling occurred in the area or not. These further studies will also provide an insight into whether the signature of neoglacial cooling in Antarctica is homogenous or regional climate fluctuations.

7. Conclusion

The study conducted using a sediment core from the Schirmacher Oasis Lake L-6 using a multiproxy approach to deduce the paleoproductivity and Holocene climate variation. The present study shows a warm phase from ~11.6 to ~10 cal ka BP (Pleistocene–Holocene boundary) with high values of BSi and Mg/Ca documenting higher paleoproductivity. The high ratio of Mn/Fe states the reducing environment due to the decomposition of organic matter in the lake bottom water. Further, the lake experienced the rapid shift from deglaciation to the glaciation at the boundary of ~10 cal ka BP. It is identified as a colder phase due to the extension of the continental ice sheet from the southward to the northward in SO from ~10 to ~3.1 cal ka BP. This period shows a lower paleoproductivity within the lake and lowers the sediment accumulation rate (~2.9 cm/ka) compared to other time periods of the Holocene. The upper part of the core section dominated by a high abundance of algal mat represents ~3.1 cal ka BP to the recent. This period showed a stepwise warming within the environment which is perfectly in correlation with the winter and summer solar insolation and stepwise increasing temperature in the East Antarctica which influence the in situ paleoproductivity in the SO. The stepwise warming evidence also substantiated by the high values of TOC, BSi, sediment accumulation rate and Mg/Ca and Mn/Fe elemental concentration ratios. This period caused the increased lake level as lakes might have received enormous melt water from the continental ice sheet and snow melt water around the lake. The presented results provide a baseline dataset for paleoclimatic history from a land locked lake of the SO and should be further confirmed by the detailed dataset generated, especially on diatom counts, so as to directly compare with the high and/or low productivity changes being presence/absence of algal mat in the core.

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